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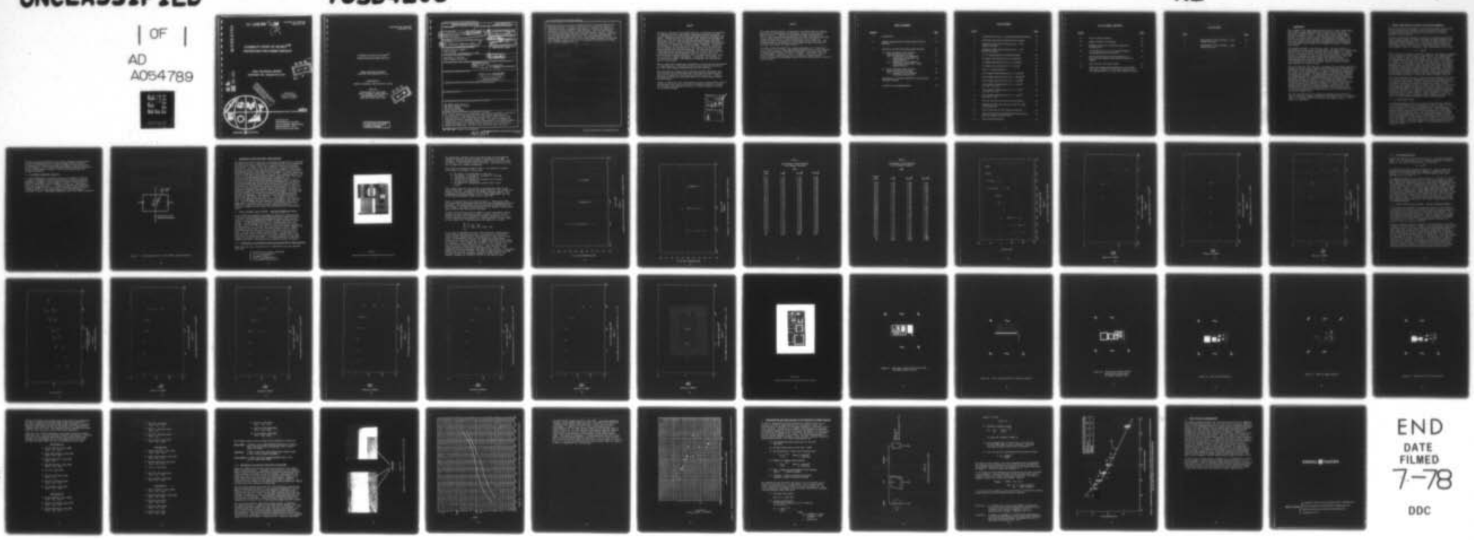

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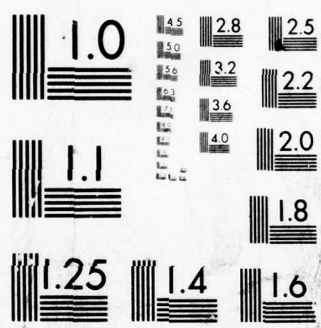
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FEASIBILITY STUDY OF GE-MOV™ PROTECTION FOR HYBRID CIRCUITS

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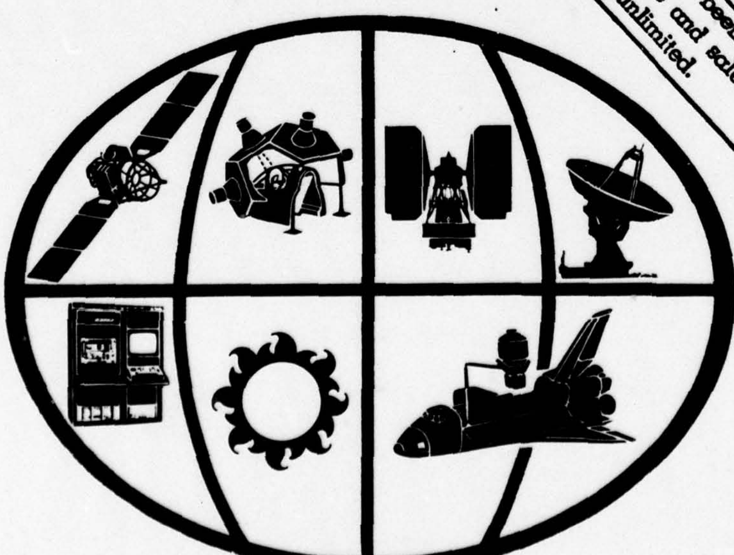
FINAL TECHNICAL REPORT
CONTRACT NO. DAAG39-76-C-0121

PREPARED BY
HUGH B. O'DONNELL
DANTE. M. TASCA



space division

PREPARED FOR
DEPARTMENT OF THE ARMY
HARRY DIAMOND LABORATORIES
2800 POWDER MILL ROAD
ADELPHI, MARYLAND 20783

GENERAL ELECTRIC

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FINAL TECHNICAL REPORT
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This report summarizes the experimental work that was performed to establish the feasibility of combining the thick film varistor technology with existing hybrid circuit technology such that useful hybrid circuit level transient protection techniques would result. In order to determine the compatibility of the thick film varistor technology with the existing hybrid circuit technology, two different thick film varistor test patterns were designed and fabricated. The first test pattern was made utilizing a

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dedicated fabrication process at General Electric Corporate Research and Development Center. The results from this test pattern were used as a baseline with which to compare later results. A second test pattern was fabricated at General Electric, Space Division. This test pattern was fabricated using an existing thick film Birox resistor process. These two test patterns were then evaluated for their electrical characteristics at DC and at one microsecond pulse width. The characteristics that were measured included the I-V curve, DC and pulse damage threshold and the long term stability. Using these results a procedure was developed to design MOV to protect hybrid circuits.

SUMMARY

The overall objective of the present work was to establish the feasibility of combining the thick film varistor technology with existing hybrid circuit technology such that useful transient protection techniques would result. Towards this end, two different test patterns were designed and fabricated. The first test pattern was fabricated using a dedicated fabrication process. The test pattern had three different area varistors printed on it of areas 0.01, 0.1 and 1 square centimeters. In addition, the thickness of the MOV was 2 mils and 4 mils. This test pattern was used to evaluate the performance of a test pattern that was fabricated using existing hybrid circuit technology. The existing hybrid circuit technology that was chosen was the process for printing Birox resistors. A test pattern was then fabricated using this process. This test pattern had five different varistors on it of areas 0.0065, 0.02, 0.065, 0.2, 0.65 and 1.5 square centimeters. In addition, the thickness of the varistor was varied. The different thicknesses that were printed were 2, 5 and 10 mils.

Both of these test patterns were evaluated for their DC and one microsecond I-V characteristics. The effect of high currents both DC and pulsed on the low voltage leakage characteristics was also evaluated.

The resulting test pattern using a dedicated process showed that thick film varistors can be fabricated that yield electrical characteristics which can be employed in the protection of hybrid circuits. A design procedure for using this thick film varistor to protect hybrid circuits was established.

Attempts to fabricate thick film varistors using an existing Birox resistor process showed that the two processes are basically compatible, however, the optimum process parameters could not be identified within the scope of the present program.

PREFACE

This Final Technical Report was prepared by the General Electric Company, Space Division, Philadelphia, Pennsylvania, under U.S. Army Contract DAAG-39-76-C-0121. The work was administered under the direction of the U.S. Army, Harry Diamond Laboratories, Lab 1000, 2800 Powder Mill Road, Adelphi, Maryland 20783. Technical monitoring of the contract at USA/HDL was under the direction of Joseph Kreck and Dr. Josip Soln. The program manager at the General Electric Company was Dante Tasca and the principal investigator was Hugh O'Donnell.

The authors wish to express their sincere appreciation to J. Kreck and Dr. J. Soln of the U.S. Army, Harry Diamond Laboratories for their technical guidance and consultation throughout the program. The authors also wish to acknowledge M. Bortulin, B. Pokol, B. Haley, F. Neff and T. Hontz of General Electric, Space Division and J. Burgess of General Electric, Corporate Research and Development Center for their contributions to the work reported herein.

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1. INTRODUCTION

This document is the Final Technical Report for U.S. Army, Harry Diamond Laboratories Contract DAAG39-76-C-0121, "Feasibility Study of MOV Protection of Hybrid Circuits". The objective of this program was to perform a feasibility study of utilizing metal oxide varistor (MOV) materials to protect hybrid circuits from electrical transients. The goal of this effort was to establish the feasibility of combining the thick film varistor technology with existing hybrid circuit technology such that useful hybrid circuit level transient protection techniques would result.

The program consisted of four distinct tasks. The first task was to establish the detailed design and fabrication requirements for incorporating MOV thick films as effective transient protection elements in a hybrid circuit. The second task was to fabricate a test pattern incorporating thick film techniques in preparing the printed MOV pattern. This test pattern was utilized in order to measure and evaluate the MOV characteristics and protective ability. The last task utilized the data from task two to show how to employ the MOV in order to protect active devices in a hybrid circuit.

The aim of the first two tasks was to determine the processing compatibility between the MOV and hybrid circuits and to fabricate and to evaluate the performance of the resulting MOV. In order to achieve these goals within the scope of this program two types of MOV test patterns were designed, fabricated and evaluated. The first pattern, which acted as a baseline for comparison purposes, was manufactured at GE Corporate Research and Development Center. This pattern was made using a dedicated fabrication process as outlined in section 3.1. The second test pattern was manufactured at GE-Space Division using the existing thick film process for Birox resistors as outlined in section 3.2. Both of these test patterns were evaluated for their performance characteristics. The characteristics which were measured included, DC I-V characteristics, the one microsecond pulse I-V characteristics and the DC and one microsecond pulse damage levels.

The last task consisted of utilizing the performance data of MOV's in order to formulate a design procedure for incorporating MOV's as protection devices in a circuit, based on the Wunsch-Bell damage constant for the device to be protected.

2. GENERAL CHARACTERISTICS OF METAL OXIDE VARISTOR MATERIALS

Before discussing the development of the thick film metal oxide varistor it will be beneficial to briefly review the principle electrical characteristics of the basic material which control its transient suppression characteristics.

The metal oxide varistor material is basically a ceramic material which offers a unique property of highly non-linear resistance (varistor) and large energy absorbing capability. The varistor, when connected in an electrical circuit, exhibits, over a wide current range, a power law relationship between the current (I) flowing through the material and the voltage (V) across the terminals. This relationship is in the form:

$$I = (V/C)^N$$

where C and N are constants, reflecting composition and geometry parameters, and are primarily a bulk property of the material. This characteristic is very similar to that of a Zener diode. Over a wide current range, the voltage remains within a very narrow band for a specific device, and is referred to as the "varistor voltage" for that device. The value of this varistor (or clamping) voltage for a particular device is linearly dependent upon the thickness of the conduction path through the device; the thicker the material, the higher the varistor voltage. The material is bipolar in that the non-linear resistance characteristic holds for both positive and negative polarity currents. Also, the bulk properties of the material provide an inherent high energy absorbing capability, because energy dissipation is evenly distributed throughout the bulk.

The varistor possesses very fast current switching characteristics, being able to switch high current subnanosecond rise time transients without any measurable time delay. Further, its electrical characteristics are a function of material properties and geometrical shape. As noted previously, the clamping voltage is a direct linear function of thickness of the material between the conduction electrodes. Because of this geometrical dependence, the application of this material as a transient protection device is quite flexible in achieving optimum configurations. The material can be readily pressed, sliced, machined, etc., into a variety of shapes; such as cylinders, disks, doughnuts, squares, and so forth, and still maintain desirable electrical characteristics.

2.1 A.C. EQUIVALENT CIRCUIT

A suitable equivalent circuit which describes the electrical operation of the varistor material for AC conditions is shown in Figure 1. The circuit consists of the parallel combination of a capacitance (due to the very thin dielectric of the intergranular phase), a high resistance leakage resistor (attributable to the high resistivity of the bismuth oxide in the intergranular phase), and a non-linear conduction element-varistor element-(associated with the intergranular phase) in series with a low resistance series resistor (due to the low resistivity of the zinc oxide grains). Any application of wire leads, etc., to the material would, of courese, result in an addition of a series inductance to the equivalent circuit in a manner similar to that associated with other electronic devices.

The bulk conduction properties of the varistor material are manifested in the V-I relationship for the varistor element shown in Figure 1. As indicated, the voltage drop across the element is linearly related to the thickness, "L", of varistor material between conducting electrodes and the current density (current "I" and cross-sectional area "A") through the material.

2.3 HIGH ENERGY ABSORPTION CAPABILITY

A critical parameter of a protection device is its ability to absorb, or bypass, the unwanted transient energy without suffering significant degradation or damage. In this regard, the GE-MOV varistor does not exhibit a catastrophic failure threshold as does, say a semiconductor device due to junction burnout. Instead, the varistor will experience a gradual degradation in its low current conduction characteristics for increasing levels of input energy pulses whose deposited energy is sufficient to cause a significant temperature rise in the varistor material.

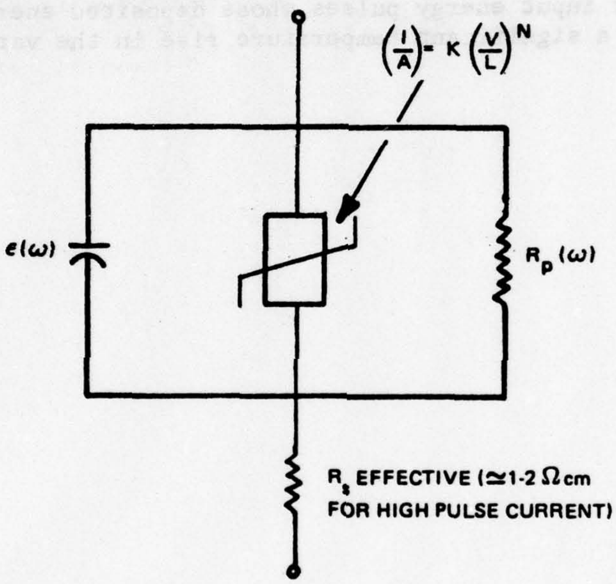


Figure 1 . AC Equivalent Circuit of the GE-MOV Varistor Material.

3. EVALUATION OF THICK FILM METAL OXIDE VARISTORS

The objective of this program was to establish the feasibility of combining the thick film varistor technology with existing hybrid circuit technology such that useful hybrid circuit level transient protection techniques would result. In order to show the feasibility of utilizing thick film varistors as hybrid circuit transient protection elements, a test pattern was fabricated using a dedicated fabrication process at General Electric, Corporate Research and Development Center (GE/CRD). This test pattern consisted of three metal oxide varistors printed on an alumina substrate. The areas of the three varistors were 0.01 CM^2, 0.1 CM^2 and 1 CM^2. The result of testing this test pattern established a baseline to which a hybrid circuit type of thick film varistor processes could be compared. The hybrid circuit type of thick film varistor process that was used was the existing thick film process for Birox resistor at General Electric, Space Division. The process for Birox resistors was used to process the thick film varistors with a minimum amount of modification in order to determine the process compatability between hybrid circuit processes and varistor processes with the scope of the present program. The thick film MOV paste material was obtained from GE/CRD as the baseline material selected for evaluation. The same thick film MOV paste material was used to make both of the test patterns. This material was made at GE/CRD by grinding MOV pellets then jet milling them to a fine particle size. This MOV powder was then mixed with a proprietary glass with 10 grams glass to 40 grams of MOV. An ethel cellulose was utilized as a binder and a pine oil solvent was used to adjust the viscosity. The different processes and the results are described in the following paragraphs.

3.1 THICK FILM METAL OXIDE VARISTOR - DEDICATED FABRICATION PROCESS

A test pattern was designed to evaluate the electrical characteristics of the thick film varistor material when printed by a dedicated process at GE-CRD. This test pattern was designed to produce thick film MOV samples in square configurations of 0.01, 0.1 and 1 centimeters square in area. Two thickness, 2 mil and 4 mil, of MOV material were also printed. This process was quite similar to the Birox resistor process. The base conductor or electrode was a platinum-gold material, Dupont #7553. This material was printed with a 200 mesh screen and fired at 1000°C. The MOV material was then printed with a 200 mesh screen and fired at 850°C. For the two mil nominal thickness MOV'S, two print-dry-fire cycles were used, while for the four mil nominal thickness MOV'S, four print-dry-fire cycles were employed. The upper conductor was the same material as the bottom electrode. The firing temperature of the upper conductor was 850°C. The resulting test pattern is shown on Figure 2.

3.1.1 Evaluation of the Dedicated Fabrication Process MOV DC Characteristics

There were five basic characteristics of these MOV'S that were measured. These were:

1) dimensional uniformity (thickness)
2) DC - I-V characteristics
3) DC damage threshold
4) Pulse I-V characteristics
5) Pulse damage characteristics

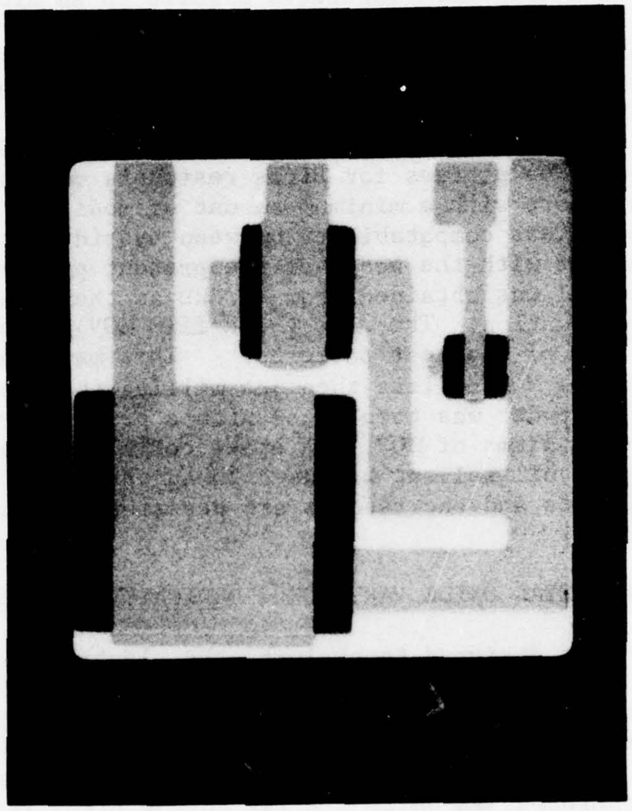


Figure 2

Dedicated Fabrication Process MOV Test Pattern

The dimensional uniformity across the test pattern is quite important because the varistor voltage is directly proportional to the MOV thickness. The thickness was measured for each of the areas (0.01 CM^2, 0.1 CM^2 and 1 CM^2) on each of thirty substrates. This was done for both the 2 mil and 4 mil nominal thicknesses.

These results are shown on Figures 3 and 4. The format for the data points shown in the graphs is as follows.

a) The symbol "*" corresponds to 1 data point.
b) The numbers "2" through "9" correspond to 2 through 9 data points respectively;
c) The letters "A" through "Z" correspond to 10 through 35 data points respectively;
d) The symbol "$" corresponds to greater than 35 data points.

These figures show that the variation in thickness was larger for the smaller area MOV'S. In addition the standard deviation was a larger percentage of the mean thickness for the thinner printing of MOV'S. The measurements are given on Tables 1 and 2. These measurements show that the MOV printing thickness varied by less than $\pm$ 10%.

The DC I-V characteristics are shown on Figure 5. These results have been normalized by graphing the volts per mil versus the amperes per square centimeter. The results shown were for conduction through the MOV from top to bottom. The results from conduction in the opposite direction were almost identical and hence were not included.

The metal oxide varistor does not exhibit a simple catastrophic failure threshold as does a semiconductor device because of junction burnout. Instead, the varistor will experience a gradual degradation in its low current conduction characteristics for increasing levels of input energy. For this reason the I-V characteristics were measured as follows:

+I, -I
+I, -I, +10I, -10I
+I, I, +10I, -10I, +100I, -100I
etc.

In this way, any degradation in low current conduction characteristics versus current level were determined. By measuring the forward and reverse current characteristics, the sensitivity of each could be determined. The measurements show that the forward and reverse damage characteristics were quite similar. The damage characteristics are shown on Figures 6-8. These figures show the graph of the ratio of the pre and post voltages at current densities of 0.01, 0.1 and 1 mA/CM^2, as a function of the DC current density stress. These figures show some slight degradation in electrical characteristics at 1 A/CM^2. This degradation is more pronounced at the lower current densities. Catastrophic damage occurs at about 10 A/CM^2. The power to cause catastrophic damage was about 300 watts per centimeter square of the MOV material. The damage was manifest by shorting of the MOV as the material melts.

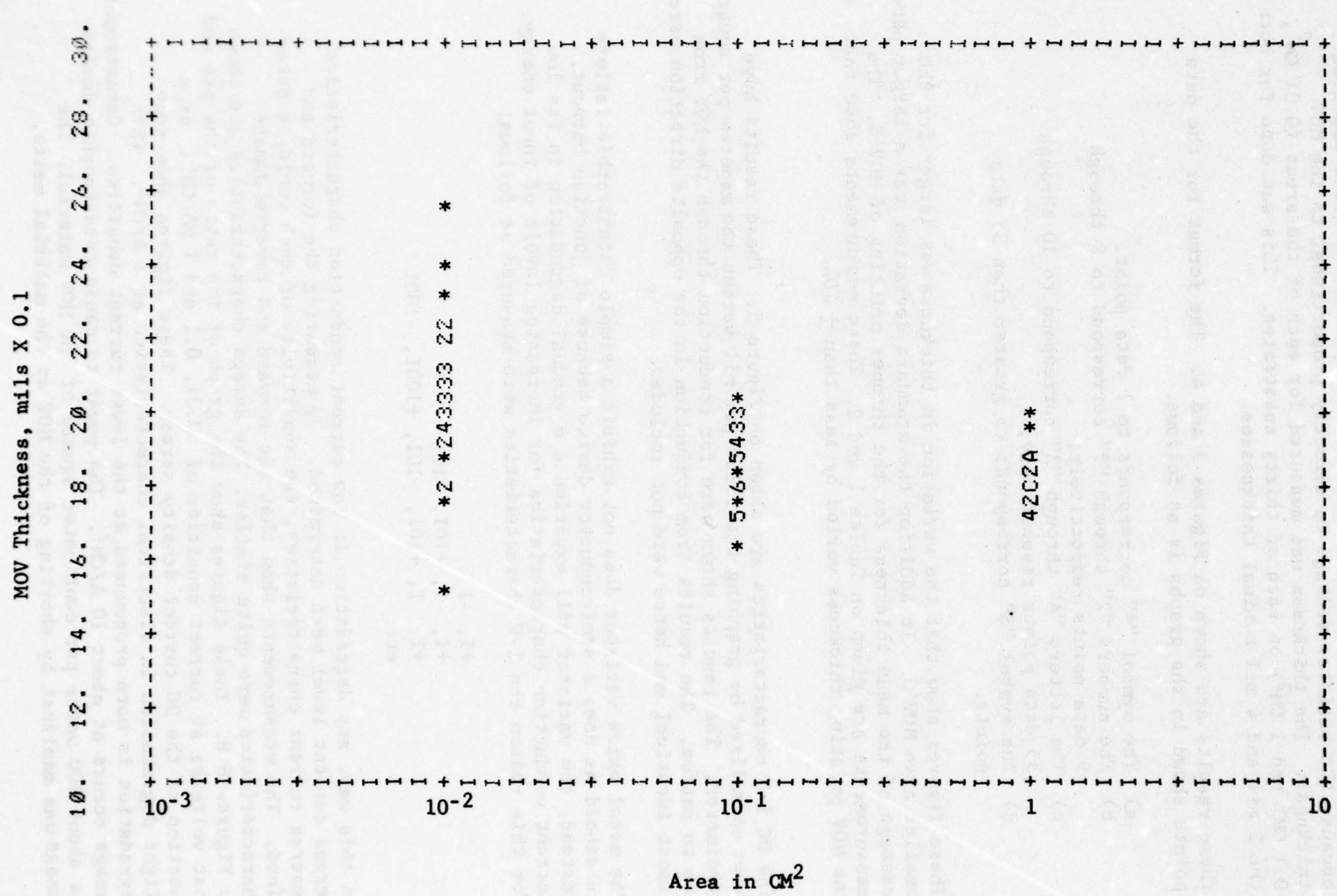


Figure 3

Thickness of MOV versus Printing Area - 2 mil Nominal Thickness

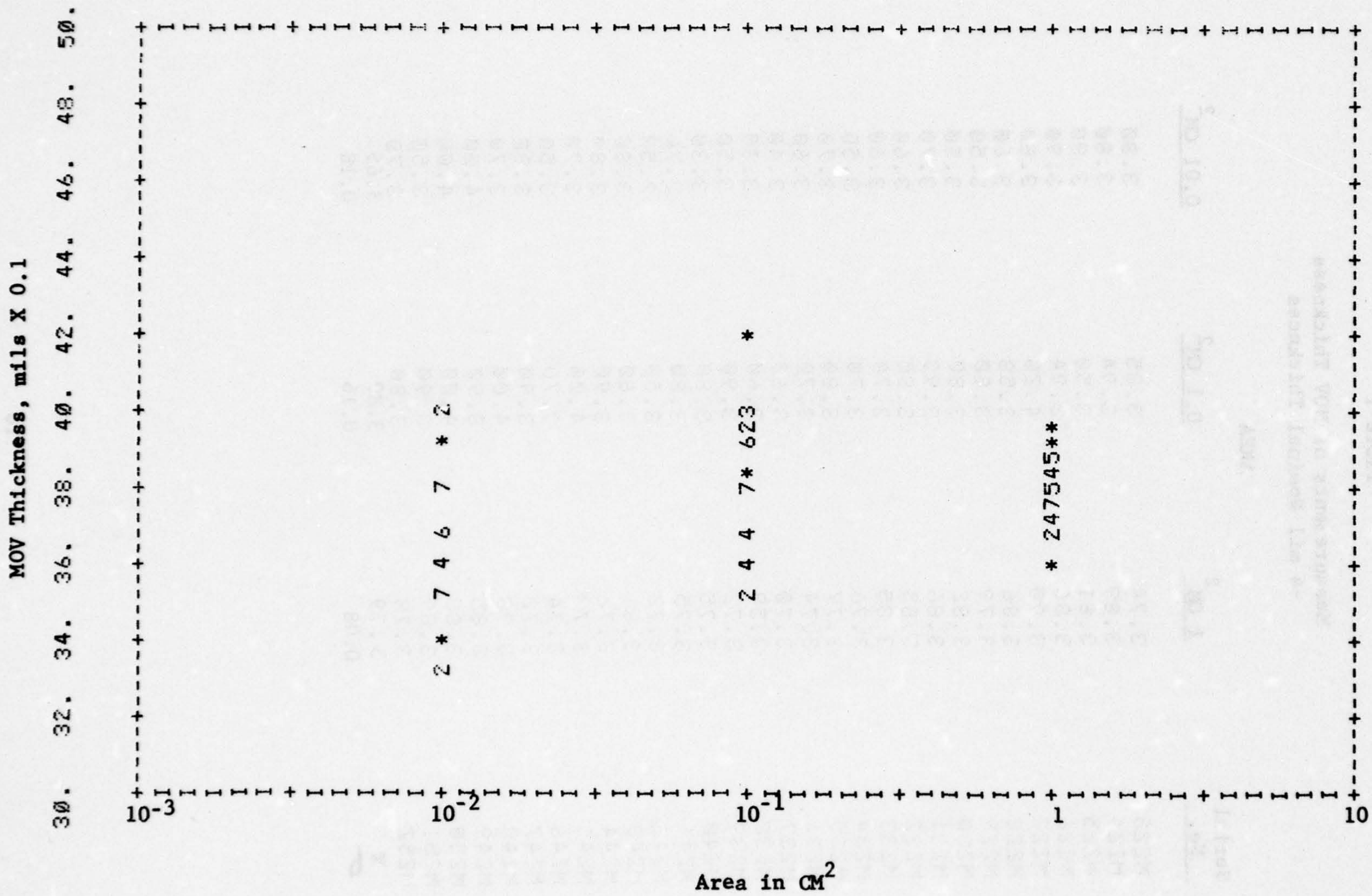


Figure 4

Thickness of MOV Versus Printing Area - 4 mil Nominal Thickness

Table 1

Measurements of MOV Thickness
-4 mil Nominal Thickness

Serial No.	AREA 1 CM^2	0.1 CM^2	0.01 CM^2
M223	3.74	3.85	3.80
M224	3.89	3.94	3.80
M225	3.81	3.50	3.80
M226	3.86	3.94	3.90
M227	3.90	4.20	3.80
M228	3.86	3.58	3.60
M229	3.79	3.80	3.50
M230	3.82	3.80	3.50
M231	3.86	3.90	3.70
M232	3.85	3.80	3.60
M233	3.85	3.70	3.60
M234	3.76	3.70	3.50
M235	3.77	3.80	3.70
M236	3.74	3.70	3.60
M237	3.70	3.60	3.40
M238	3.58	3.60	3.30
M239	3.72	3.90	3.50
M240	3.75	3.80	3.30
M241	3.75	3.80	3.70
M242	3.72	3.50	3.50
M243	3.81	3.60	3.80
M244	3.72	3.90	3.80
M245	3.73	4.00	3.70
M246	3.74	3.70	3.50
M247	3.70	3.90	3.80
M248	3.98	4.00	3.70
M249	3.85	3.90	4.00
M250	3.83	4.00	4.00
M251	3.89	3.90	3.50
M252	3.78	3.80	3.70
$\bar{x}$	3.79	3.80	3.65
σ	0.08	0.16	0.18

Table 2

Measurements of MOV Thickness
-2 mil Nominal Thickness

AREA

Serial No.	1 CM^2	0.1 CM^2	0.01 CM^2
M190	1.98	2.02	2.24
M191	1.85	1.86	2.12
M192	1.74	1.80	2.08
M193	1.86	1.78	2.10
M194	1.78	1.88	2.02
M195	1.80	1.64	1.88
M196	1.82	1.94	2.12
M197	1.83	1.94	2.30
M198	1.71	1.74	1.90
M199	1.78	1.84	2.40
M200	1.82	1.88	2.20
M201	1.86	1.94	1.96
M202	1.87	1.72	2.12
M203	1.89	1.80	2.08
M204	1.86	1.90	2.00
M205	1.82	1.78	2.04
M206	1.95	1.90	1.80
M207	1.77	1.88	1.94
M208	1.81	2.00	2.56
M209	1.89	1.72	1.78
M210	1.87	2.00	2.22
M211	1.78	1.76	1.76
M212	1.73	1.82	1.96
M213	1.73	1.82	2.20
M214	1.86	1.90	1.96
M215	1.78	1.74	1.92
M216	1.76	1.88	1.50
M217	1.79	1.80	2.02
M218	1.87	1.70	2.00
M219	1.79	1.90	2.00
$\bar{x}$	1.82	1.85	2.039
σ	0.063	0.098	0.204

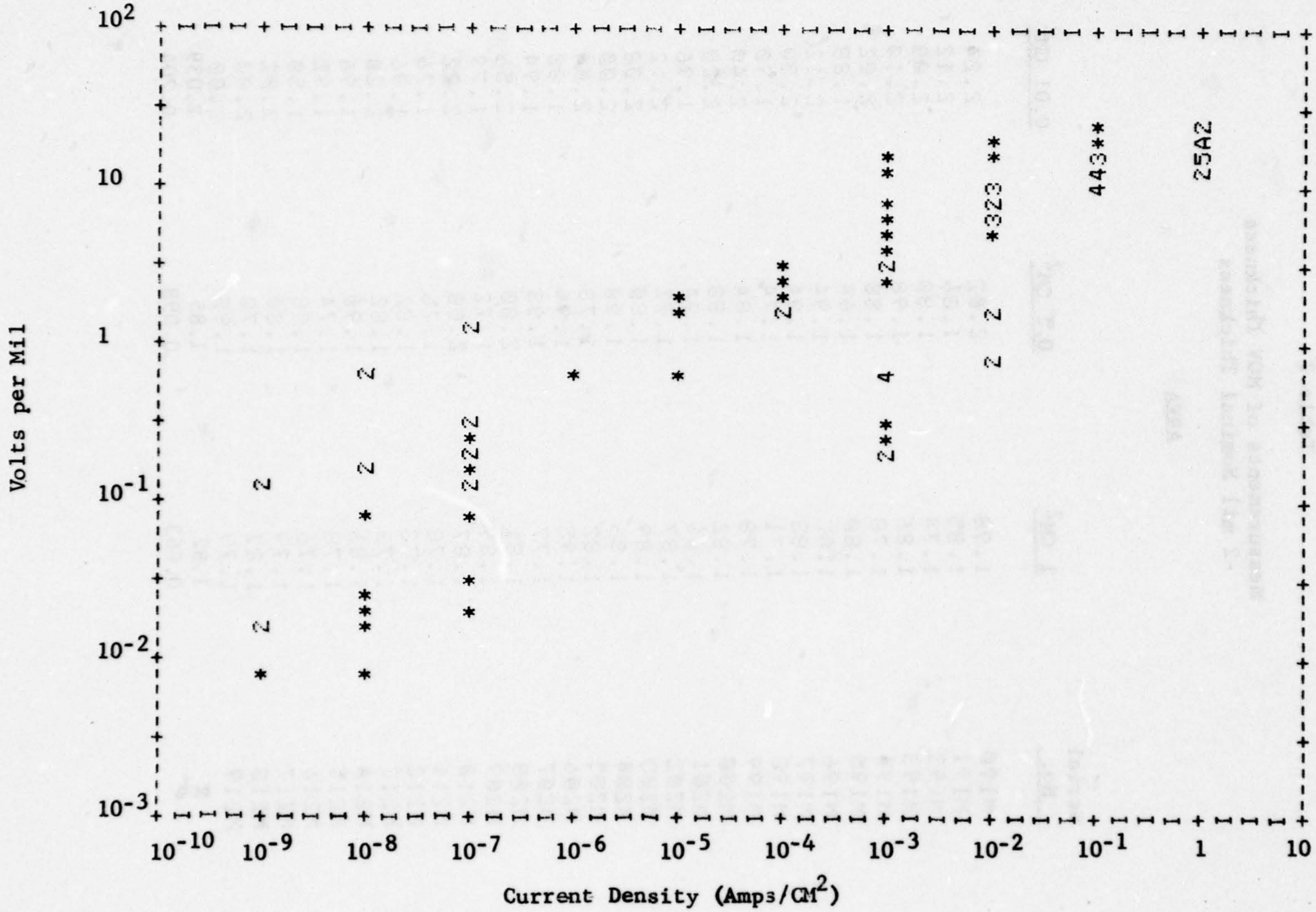


Figure 5

DC I-V Characteristics of Thick Film MOVS

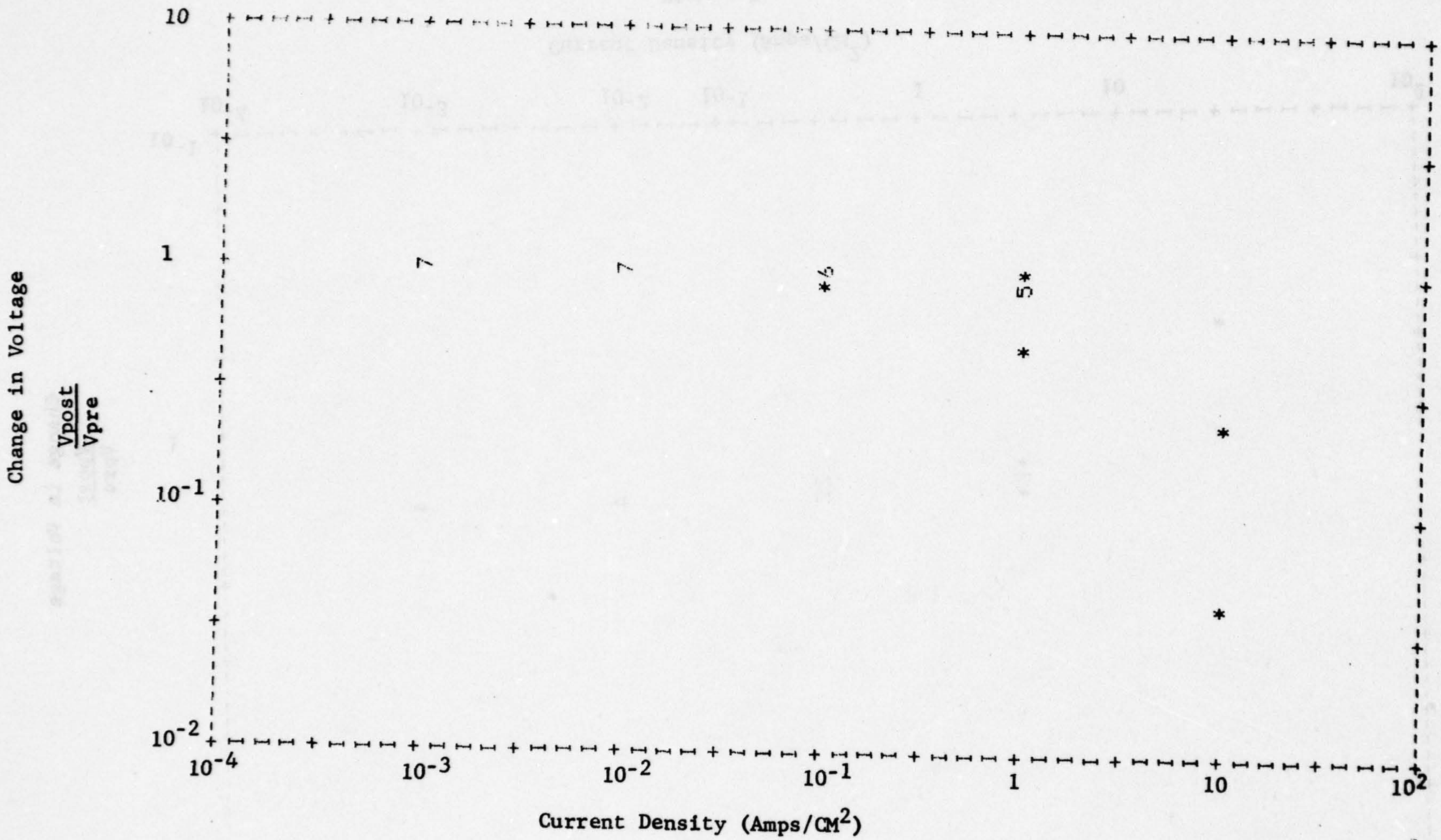


Figure 6

DC Damage Characteristics at I = 10 $\mu A/CM^2$

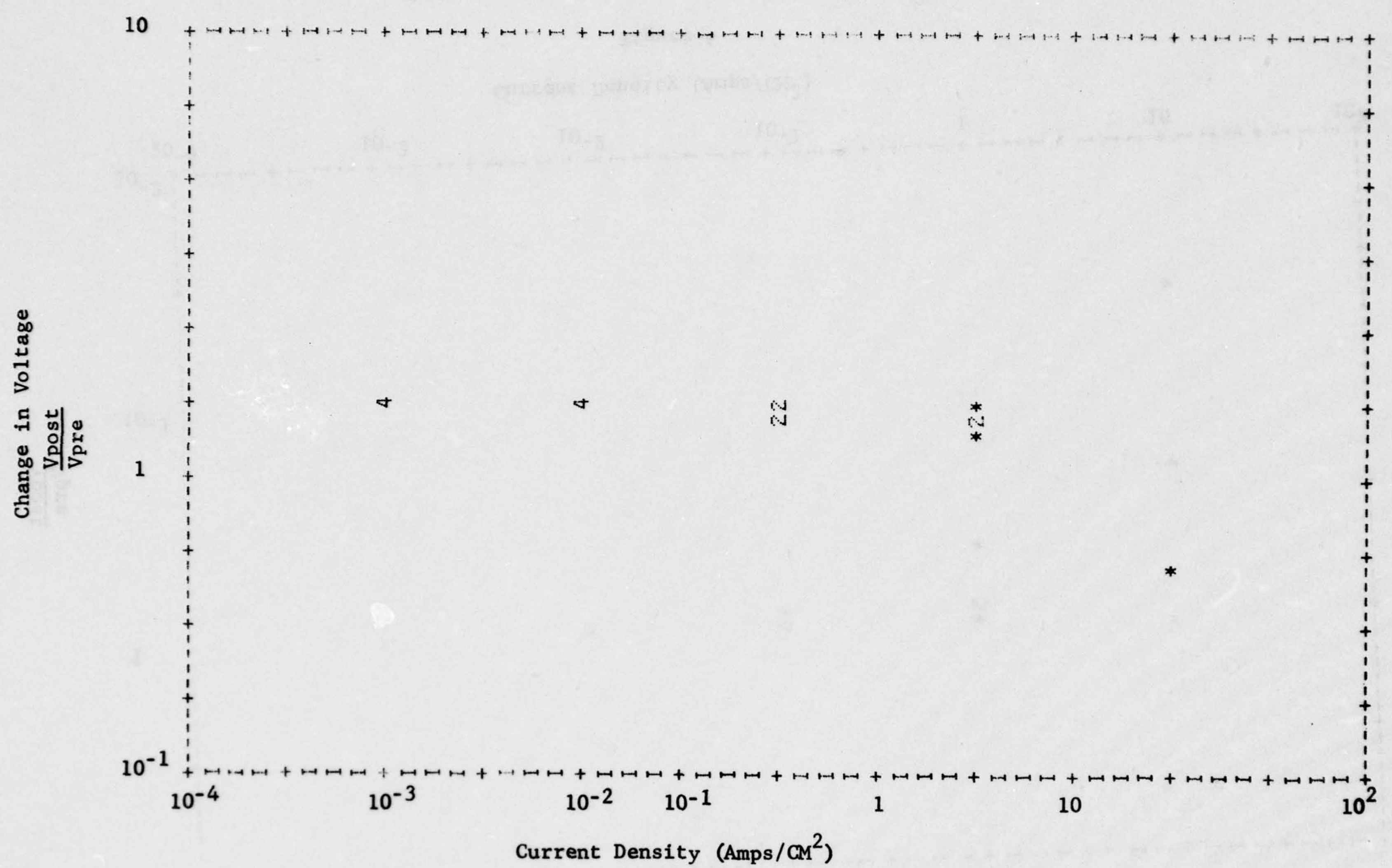


Figure 7

DC Damage Characteristics at $I = 0.1\ mA/CM^2$

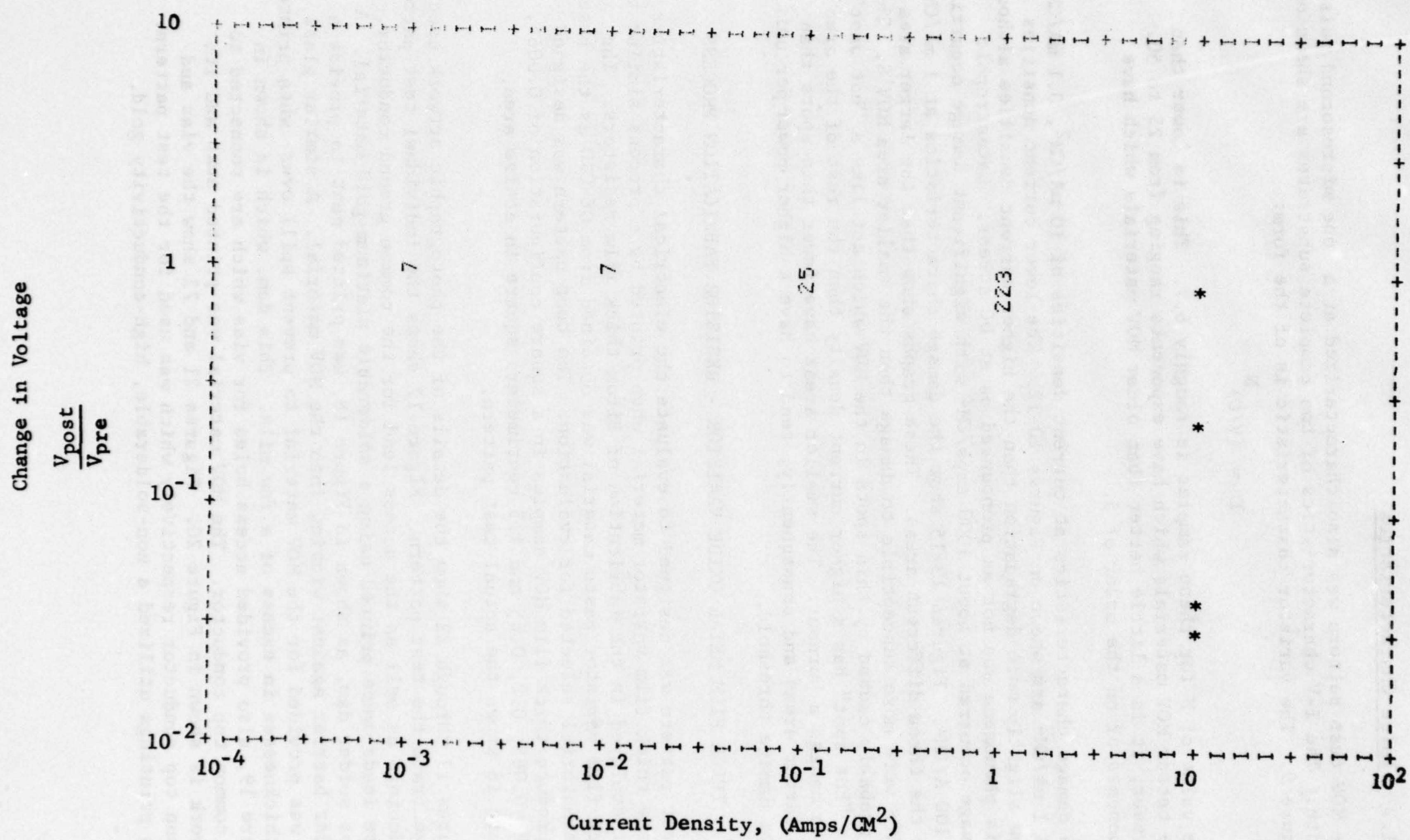


Figure 8

DC Damage Characteristics at $I = 1\ mA/CM^2$

3.1.2 Pulse Characteristics

The MOV test pattern was also characterized at a one microsecond pulse width. The I-V characteristics of two complete substrates are shown on Figure 9. The varistor characteristic is of the form:

$$I = (V/C)^N$$

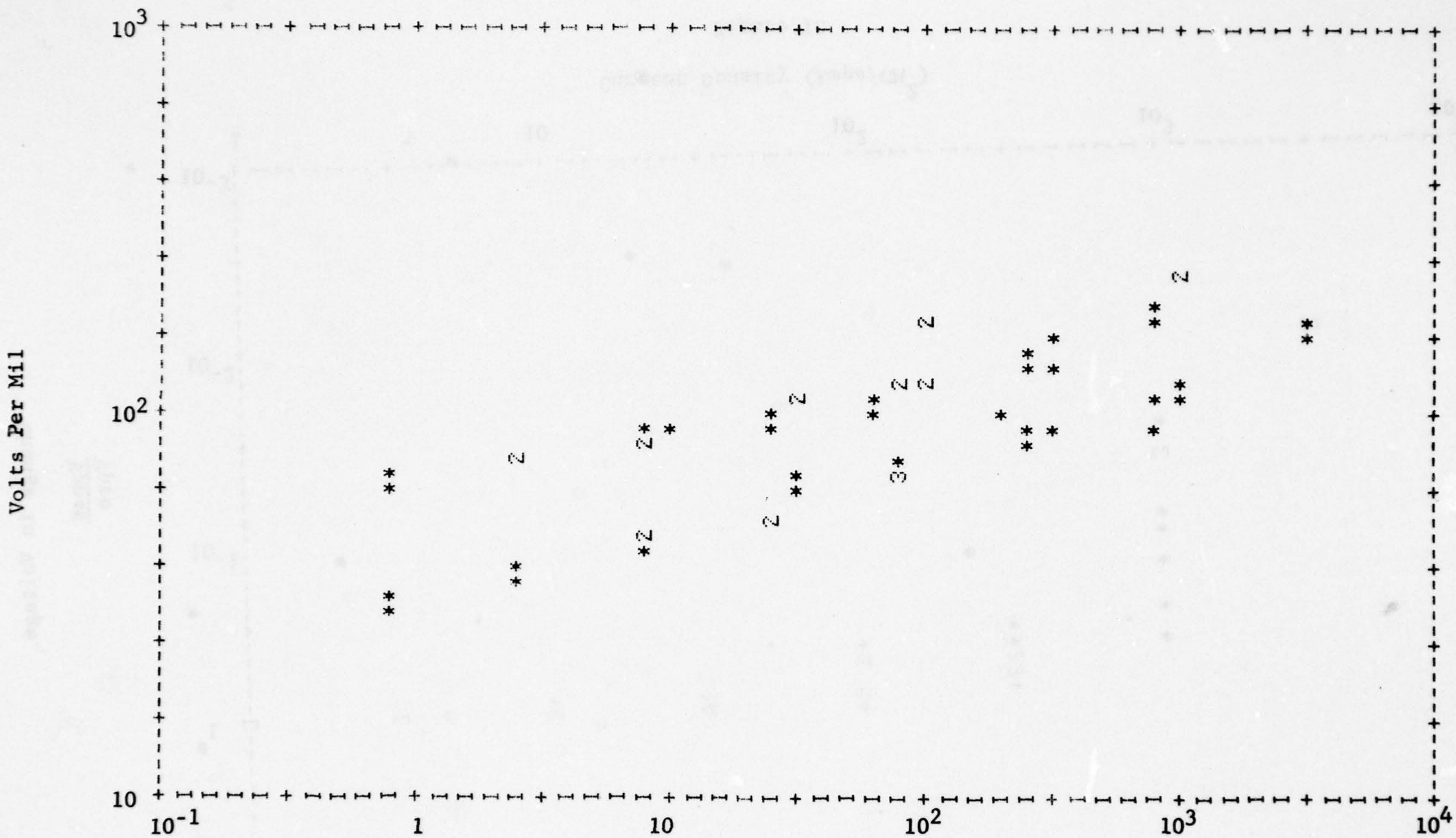
The value of N for these samples is roughly 6.7. This is lower than the better MOV materials which have exponents ranging from 25 to 50. However, it is a little better than older MOV materials which have exponents of on the order of 5.

The damage characteristics at current densities of 10 $\mu A/CM^2$, 0.1 mA/CM^2 and 1 mA/CM^2 are shown on Figures 10-12. The lower current densities show slightly more degradation than the higher current densities although this phenomena was not as pronounced as at DC stress. Catastrophic damage occurred at about 1000 $amps/CM^2$ with significant damage occurring at 100 A/CM^2. Figures 13-15 show the damage characteristics at 1 mA/CM^2 for the three different areas. These graphs show that the larger area MOV'S were more susceptible to damage than the smaller area MOV'S. This is probably caused by thin spots in the MOV which act like a "hot spot". This "hot spot" has a higher current density than the rest of the area which causes a burnout. The smaller areas have fewer thin spots than the larger areas and consequently, tend to have a higher power per unit area damage threshold.

3.2 THICK FILM METAL OXIDE VARISTOR - RESISTOR FABRICATION PROCESS

A test pattern was designed to evaluate the electrical characteristics of the thick film varistor material when printed by a process similar to that employed in the fabrication of Birox thick film resistors. The thick film varistor paste material was obtained from GE-CRD as the baseline material selected for evaluation. The test pattern was designed to produce thick film MOV samples in a square configuration of 0.0065, 0.02, 0.065, 0.2, 0.65 and 1.5 centimeters square in active area. Figure 16 shows the actual test pattern.

Figures 17 through 22 show the details of the photographic artwork used to generate the test pattern. Figure 17 shows the individual test pattern conductors as well as the access lead for the common ground conductor. These leads were printed using a solderable platinum-gold material. A glass solder dam, as shown in Figure 18, was printed next to provide a solder barrier against wicking into the MOV material. A similar glass dam was provided for the MOV material to prevent spill over when printed in thicknesses in excess of a few mils. This dam, which is shown in Figure 19, also provided access holes for vias which are connected to the common top conductor. The MOV material was printed next and its artwork is shown in Figure 20. Figures 21 and 22 show the vias and common top conductor respectively which was used for the test pattern. Both printings utilized a non-solderable, high-conductivity gold.



Current Density (Amps/CM^2)
One Microsecond

Figure 9

Pulse I-V Characteristics

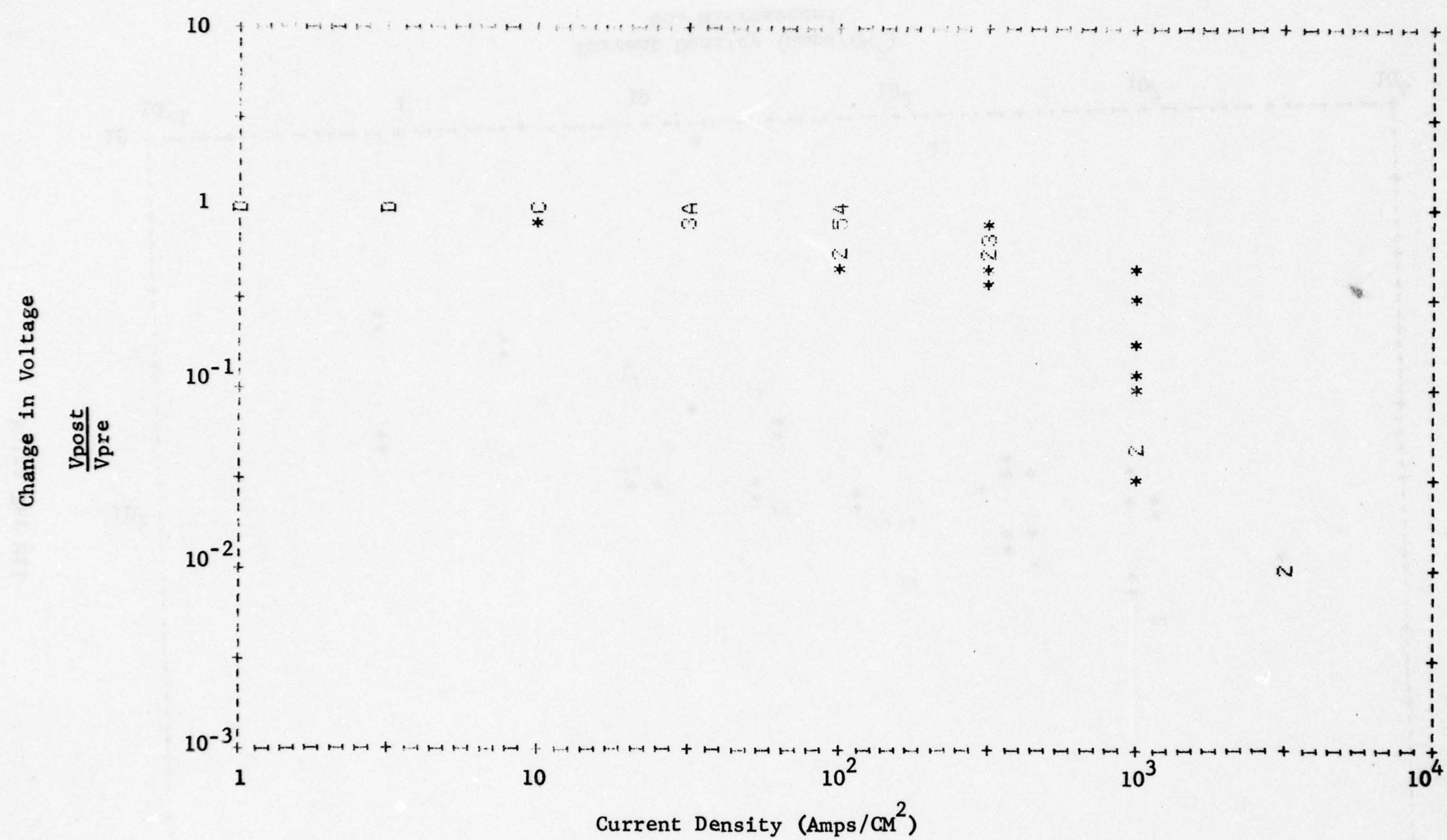


Figure 10

Pulse Damage Characteristics at I = 10 $\mu A/CM^2$

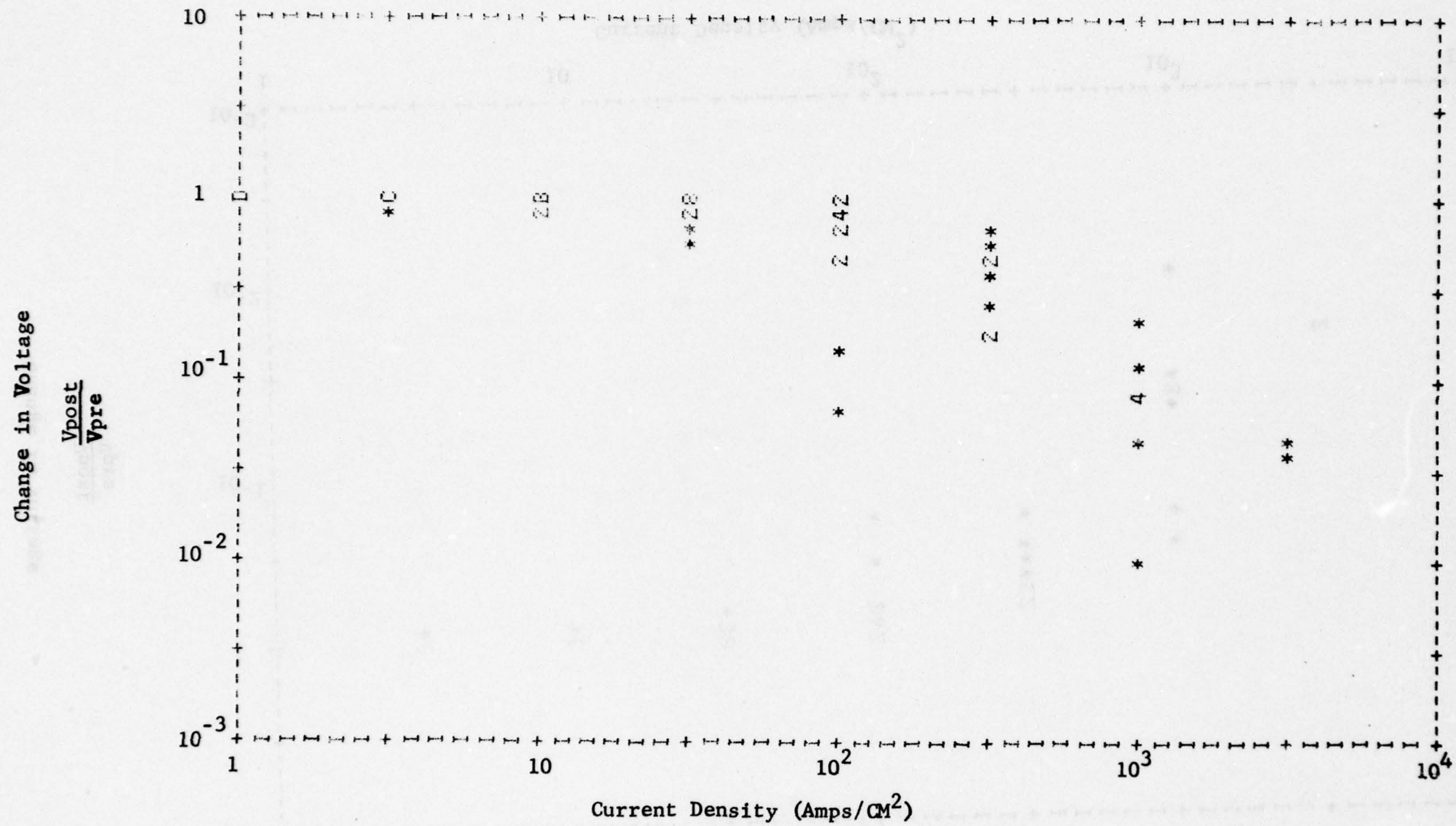


Figure 11

Pulse Damage Characteristics at I = 100 μA/CM^2

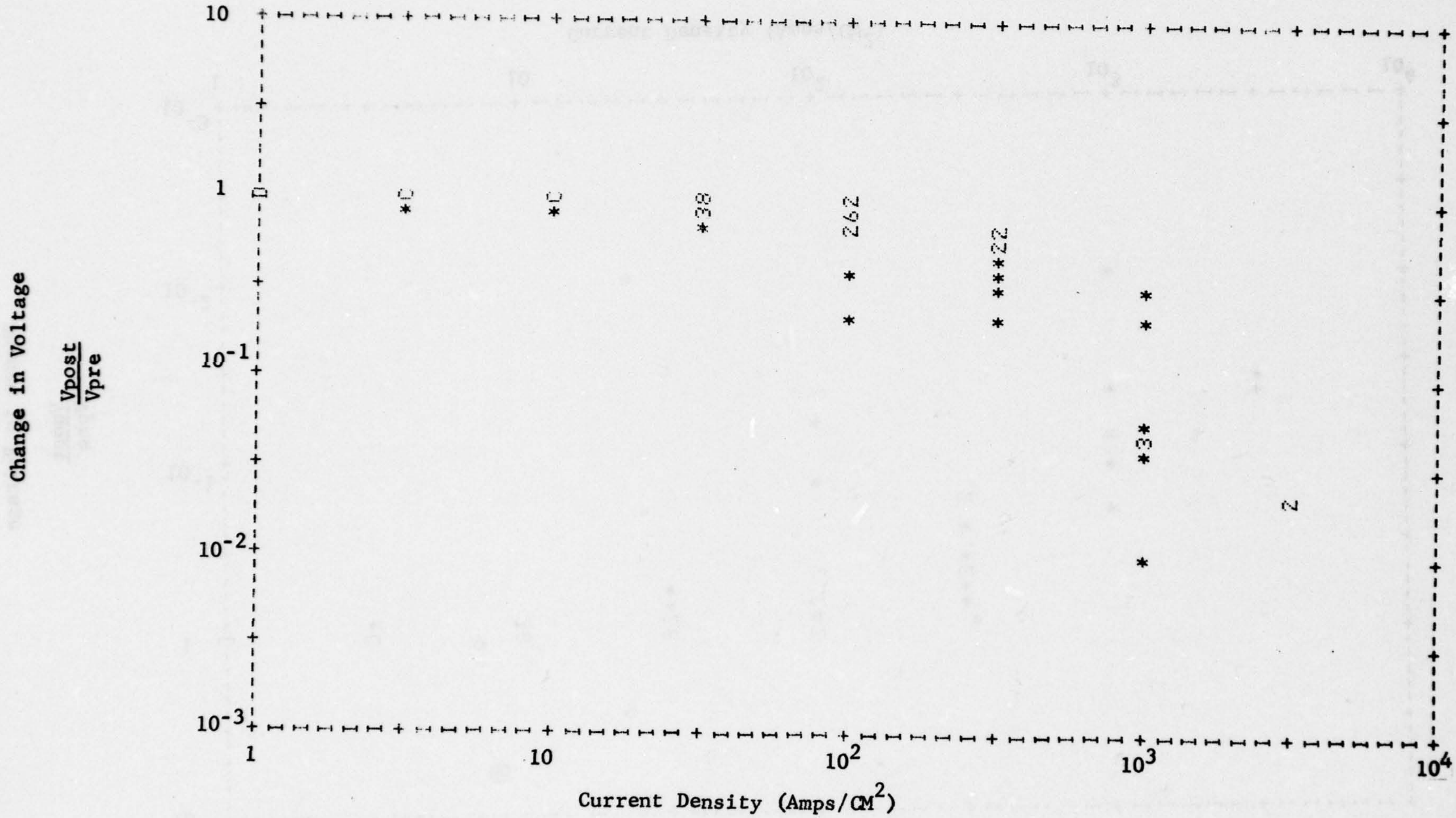


Figure 12

Pulse Damage Characteristics at I = 1 mA/CM^2

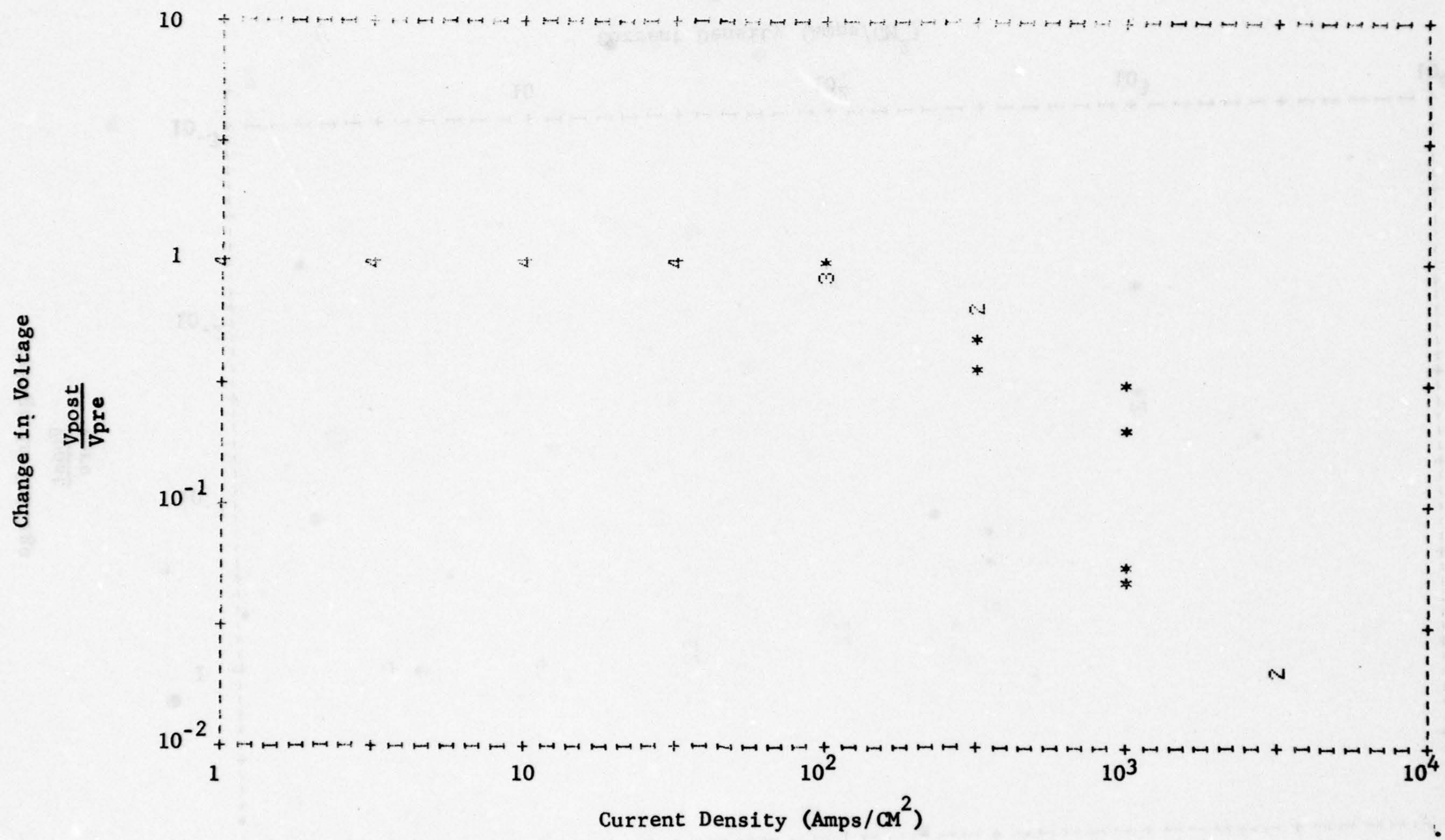


Figure 13

Pulse Damage Characteristics at $I = 1\ mA/CM^2$ for Area = $0.01\ CM^2$

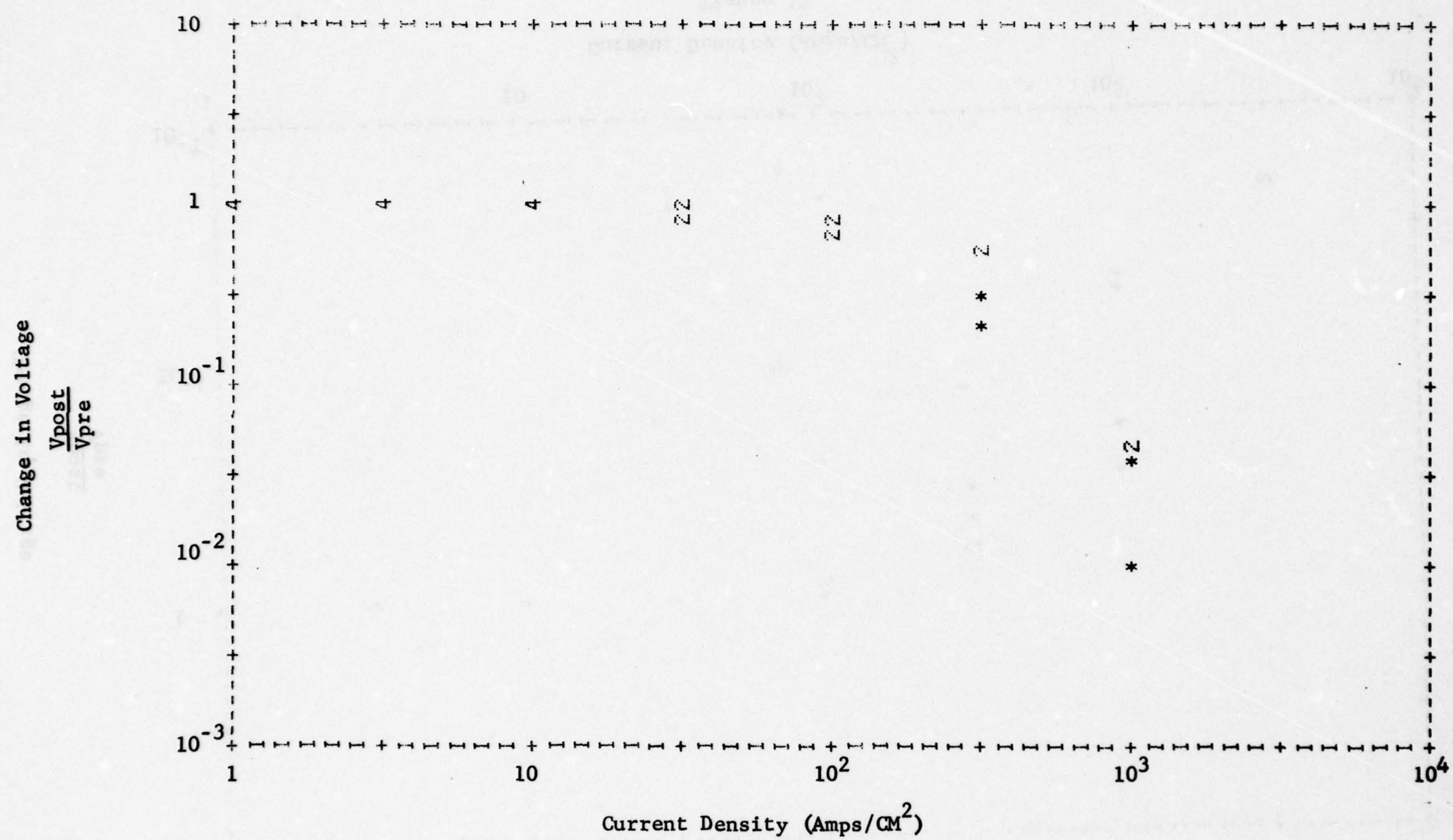


Figure 14

Pulse Damage Characteristics at 1 mA/CM^2 for Area - 0.1 CM^2

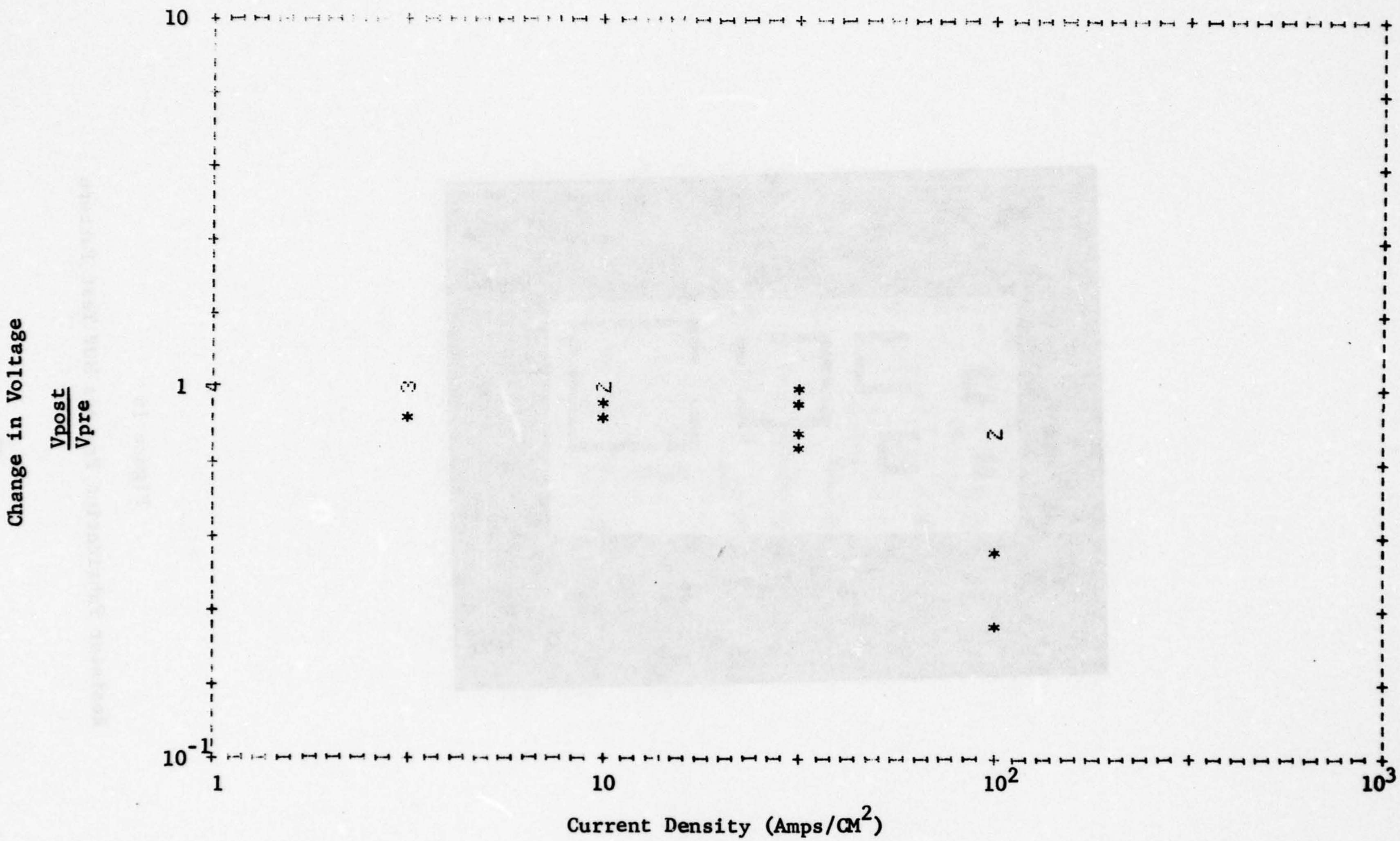


Figure 15

Pulse Damage Characteristics at 1 mA/CM^2 for Area = 1 CM^2

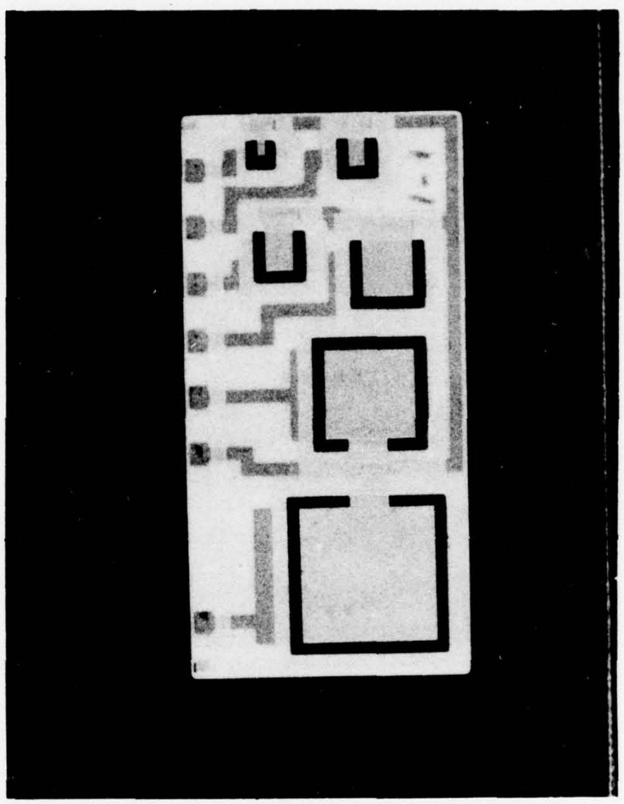


Figure 16

Resistor Fabrication Process MOV Test Pattern

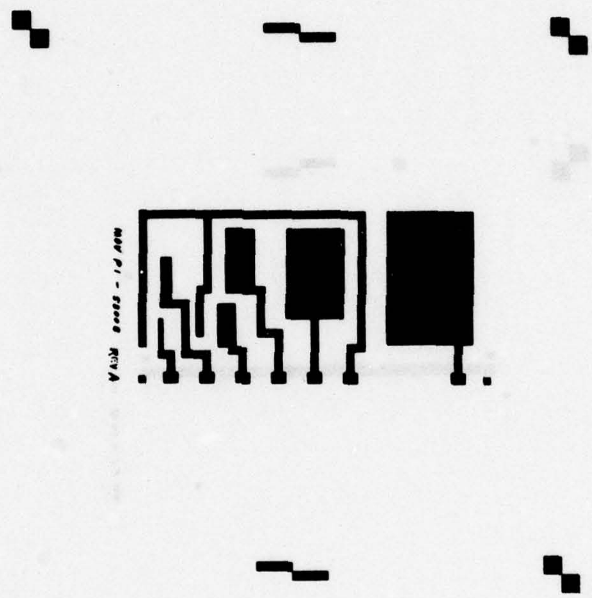


Figure 17. Individual Conductors and Access Lead For Common Ground Conductor

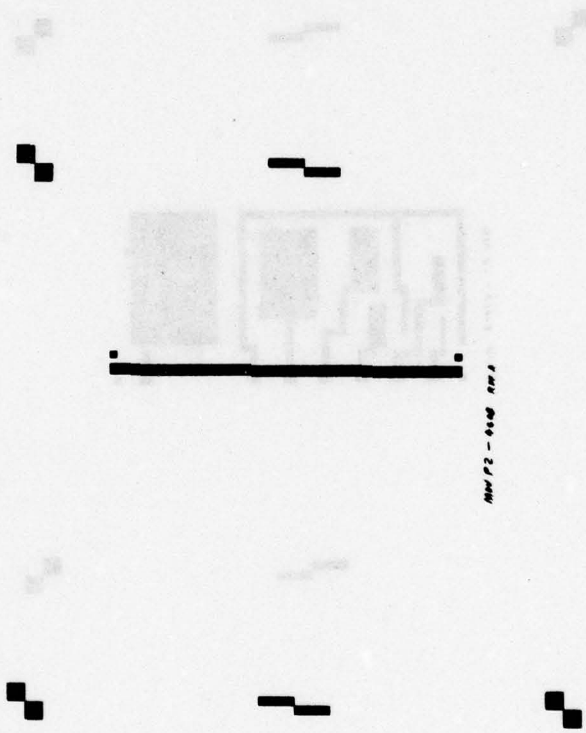


Figure 18. Glass Solder Dam For Test Pattern Conductors

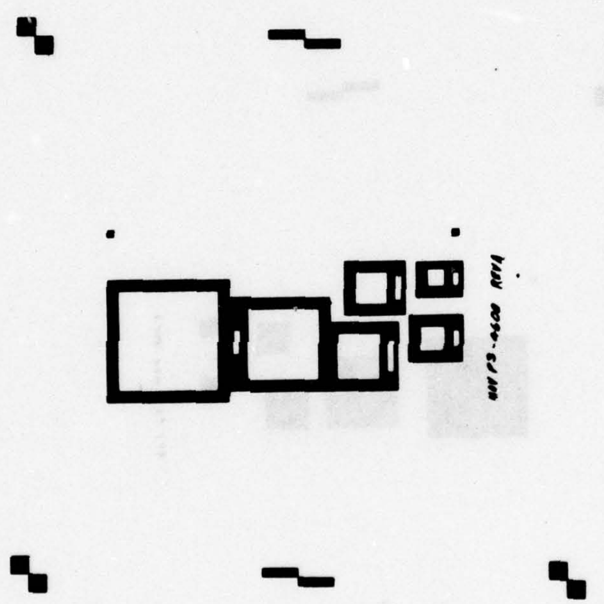


Figure 19. Glass Dam For Thick Film MOV
Material With Access Holes
For Common Conductor Vias.

Figure 20. Thick Film MOV Patterns

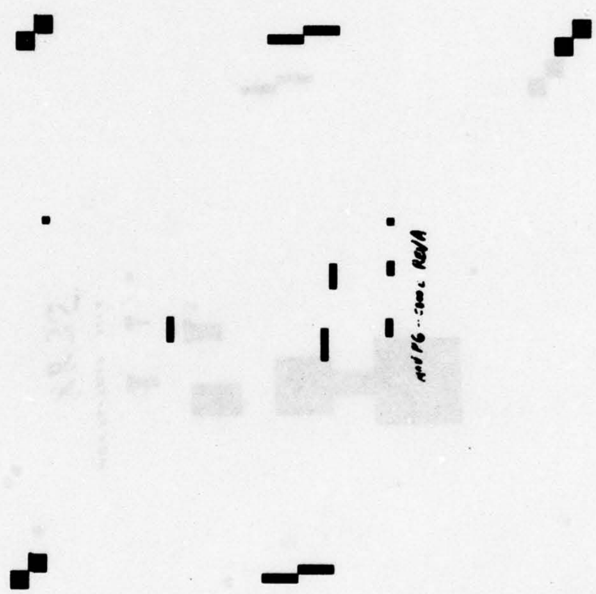


Figure 21. Vias For Common Conductor

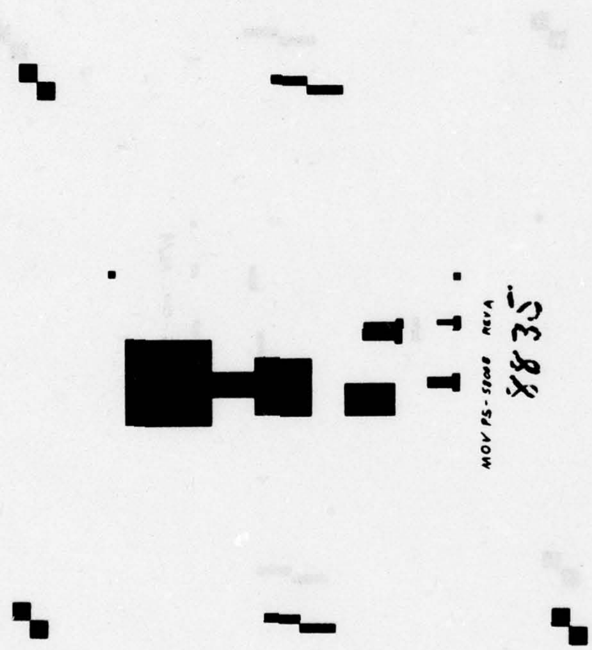


Figure 22. Common Conductor For Test Pattern

Initial test samples were printed using screens which yield thicknesses of 2 mils, 5 mils and 10 mils when used to print Birox resistors. The thick film material consisted of MOV powder suspended in a Hercules Terpineol # 318 binder and had a solids content of 78.5 percent after firing at 750°C for ½ hour. This paste was used as received and printed using the Birox resistor process of 850°C peak temperature.

There were four different variations to the basic process as outlined. There were 2 mil, 5 mil and 10 mil MOV thickness test patterns. Moreover, for the 2 mil test pattern the MOV and the top conductor were fired separately for some samples and for other samples they were cofired. The exact processing steps for the four patterns were as follows.

MOV Process A1

1) Bottom conductor, paste 5800B
Print - Dry - Fire

2) Glass dam insulator, paste 4608
Print - Dry - Fire

3) MOV dam insulator, paste 4608
Print - Dry

4) MOV dam insulator, paste 4608
Print - Dry - Fire

5) Via fill, paste 8835

6) MOV fill, 200 mesh screen
Print - Dry

7) MOV fill, 200 mesh screen
Print - Dry - Fire

8) Top Conductor, paste 8835
Print - Dry - Fire

MOV Process A2

1) Bottom conductor, paste 5800B
Print - Dry - Fire

2) Glass dam insulator, paste 4608
Print - Dry - Fire

3) MOV dam insulator, paste 4608
Print - Dry - Fire

4) Via Fill, paste 8835
Print - Dry - Fire

5) MOV fill, 200 mesh screen
Print - Dry

6) MOV fill, 200 mesh screen
Print - Dry

7) Top conductor, paste 8835
Print - Dry - Fire

MOV Process B

1) Bottom Conductor, paste 5800B
Print - Dry - Fire

2) Glass dam insulator, paste 4608
Print - Dry - Fire

3) MOV dam insulator, paste 4608
Print - Dry - Fire

4) Via fill, paste 8835

5) MOV fill, 180 screen mesh
Print - Dry - Fire

6) Top conductor, paste 8835
Print - Dry - Fire

MOV Process C

1) Bottom conductor, paste 5800B
Print - Dry - Fire

2) Glass dam insulator, paste 4608
Print - Dry - Fire

3) MOV dam, paste 4608
Print - Dry - Fire

4) Via fill, paste 8835
Print - Dry - Fire

5) MOV dam, paste 8835
Print - Dry - Fire

6) Via fill, paste 8835
   Print - Dry - Fire

7) MOV fill, 180 screen mesh
   Print - Dry - Fire

8) Top conductor, paste 8835
   Print - Dry - Fire

The different pastes that are called out in the process outline are:

Paste 5800B - A general purpose high adhesion platinum-gold conductor made by Electro-Science Laboratories (ESL), material number ESL-5800B.

Paste 8835 - A highly conductive, high density gold conductor made by ESL, material number ESL-5800B.

Paste 4608FB- A ceramic dielectric coating material made by ESL, material number ESL-4608FB.

3.2.1 Evaluation of the Resistor Fabrication Process MOV

These test samples were evaluated after printing and all were found to exhibit electrical shorts. Subsequent failure analysis by the General Electric, Space Division Microelectronics Laboratory revealed that microscopic pinholes were present in the test pattern. These pinholes were judged to be due to the low viscosity of the MOV paste relative to the wiper speed and pressure employed in the Birox process. Examples of these pinholes and cracks in these samples are shown in Figure 23. As a result of these observations the thick film printing process was changed and additional test patterns were fabricated.

The new process entailed using only the 5 mil screen and a pre-selected paste viscosity which yielded a 2.5 mil per print thickness for the MOV material. The MOV paste viscosity was changed by adding additional liquid binder until the desired 2.5 mil print thickness for the MOV was obtained. In addition to this, two different print procedures were also used for the test patterns. Each procedure, furthermore, employed two printings for the MOV paste. Process #1 used a "print-dry-print-fire" sequence while process #2 used a "print-dry-fire-print-dry-fire" sequence.

This new process yielded significantly better results as compared to the original process. A number of electrical shorts, however, were still observed in the three largest area test cells for both processes. It is felt that additional reductions in paste viscosity would produce much better yields as well as improved device characteristics from that described below. The devices which were fabricated from the new process were capable of sustaining a 1 ma/CM^2 DC current density without permanent damage to their low current V-I characteristics. Material capacitance

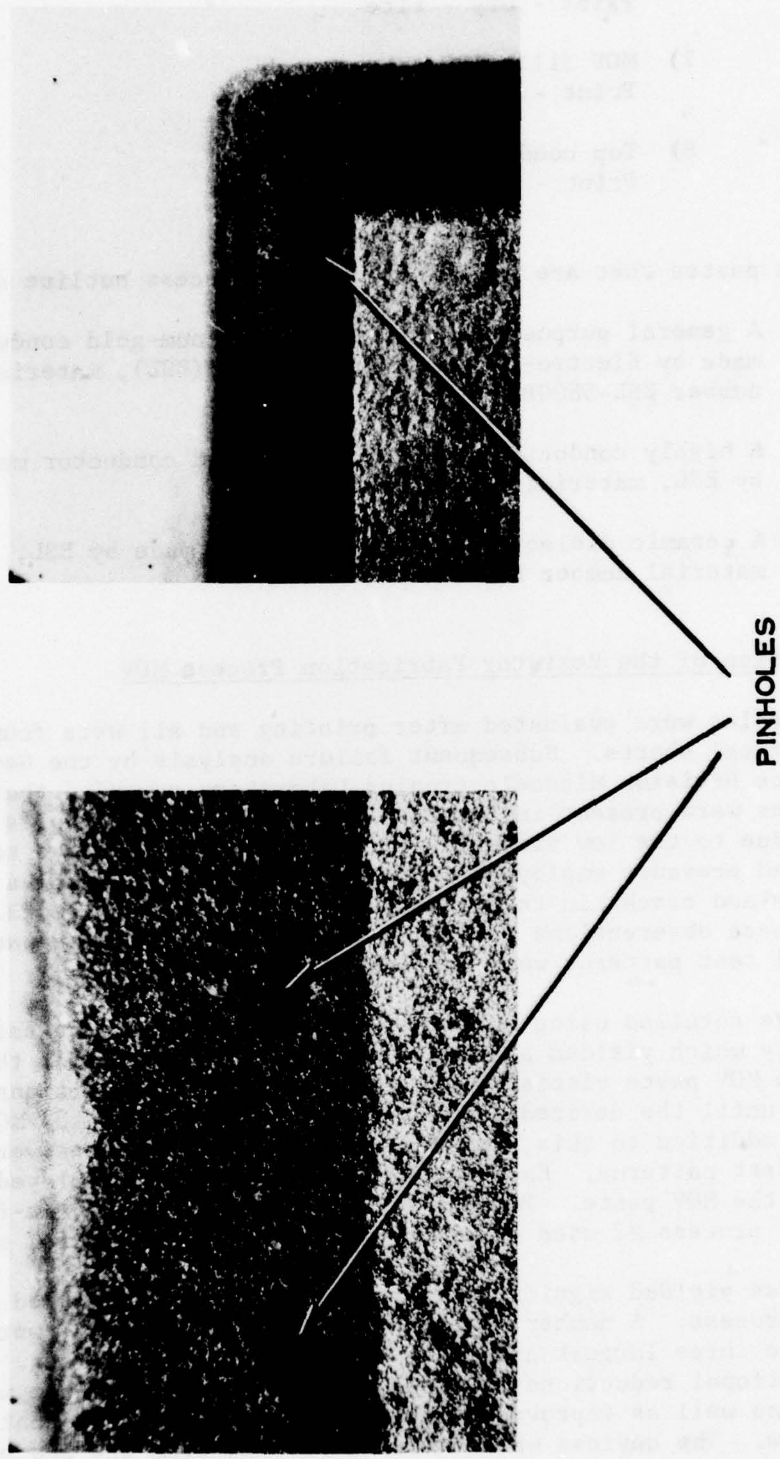


Figure 23

Examples of Pinholes in Resistor Fabrication Processed MOV

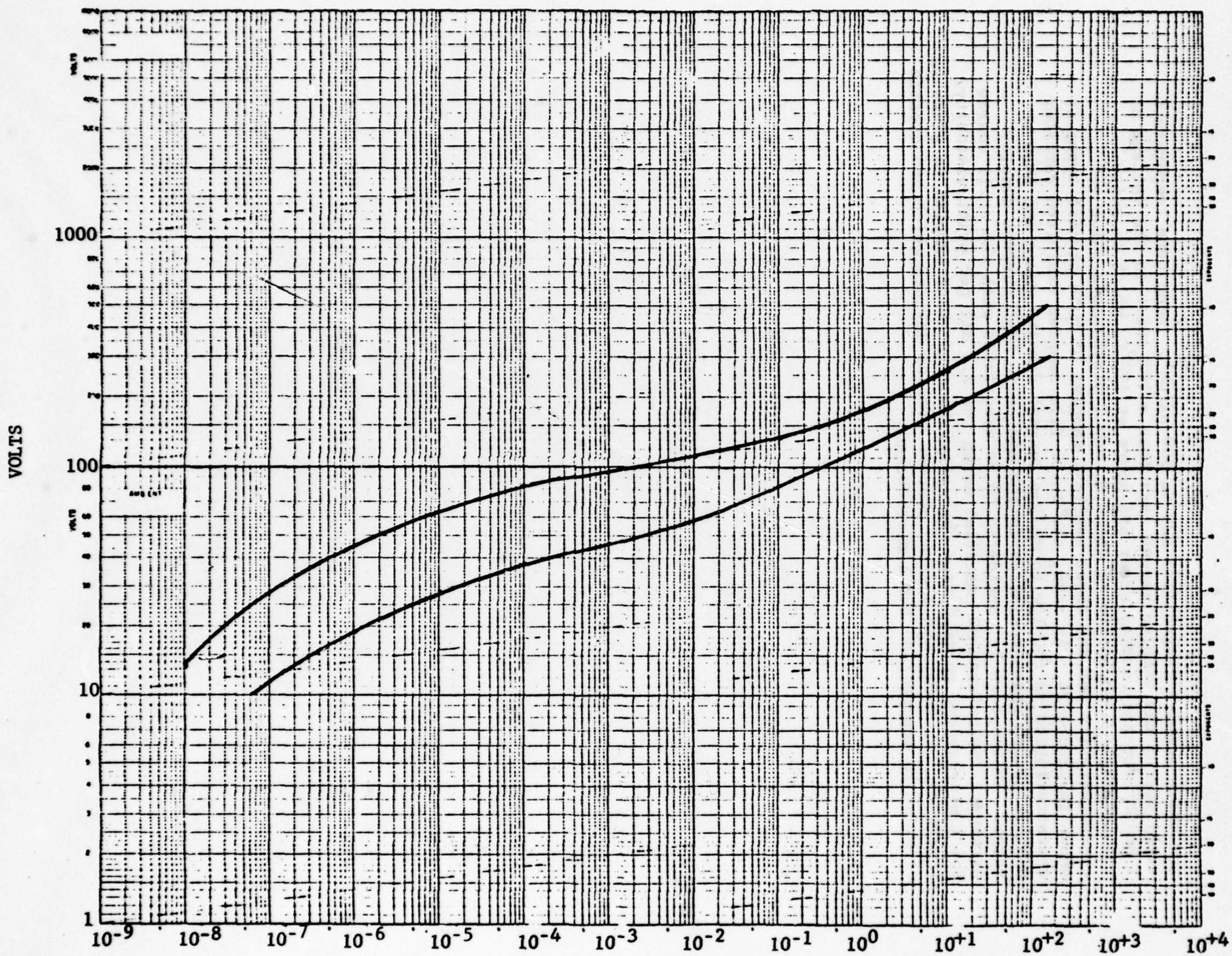


Figure 24. V-I Characteristics of Thick Film MOV Samples Using Updated Fabrication Process

for these samples ranged from 400 to 600 pf/CM^2. Long term temperature stability of the samples showed less than a 10% shift in the voltage at 1 ma/CM^2 current density after 696 hours at 125°C, which is quite encouraging. A composite of the D.C. and 1 microsecond pulse V-I characteristics for the three smallest samples of both process types is shown in Figure 24. As seen, the thick film samples exhibited varistor characteristics in the low to medium current density range and then exhibit upturn characteristics in the medium to high current density range. This upturn is considered to be associated with the still coarse nature of the printed MOV material using the 2.5 mil per print viscosity. The 1 microsecond pulse damage characteristics of these samples is given in Figure 25. As seen, the updated process yielded devices which are capable of about 10 amperes/CM^2 for 1 microsecond.

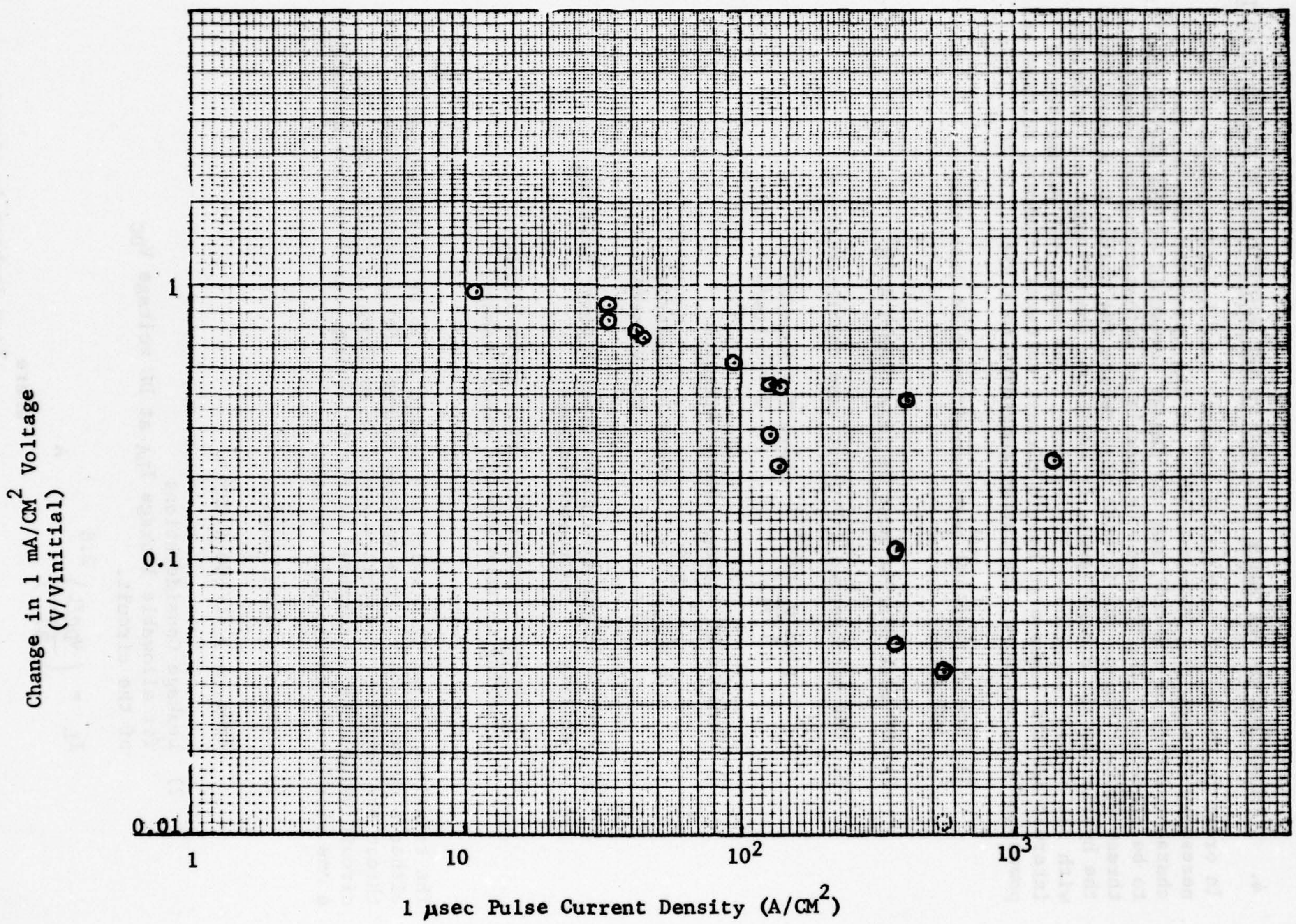


Figure 25. One Microsecond Pulse Current Capability of Thick Film MOV Samples Using Updated Fabrication Process

4. APPLICATION OF THE THICK FILM MOV TO THE PROTECTION OF HYBRID CIRCUITS

In order to design MOV protection elements into hybrid circuits it is necessary to know the characteristics of the transient threat, the characteristics of the MOV, and the damage threshold of the device that is to be protected. The MOV must be capable of withstanding the transient threat without damage and it must also reduce the threat to a level below the hybrid circuit damage level. In addition, the MOV must not interfere with the normal operation of the circuit. The basic MOV parameters of interest are the leakage at hybrid circuit voltages, clamping voltage and power handling ability. The design considerations are:

1) One microsecond peak current must be less than 100 A/CM^2.

2) DC peak current must be less than 1 A/CM^2.

3) One microsecond I-V worst case characteristics:

$$I = \left(\frac{V}{71}\right)^{6.7} \quad \text{where } I = \text{Amps}/CM^2, \; V = \text{Volts/mil}$$

4) Nominal DC leakage characteristics

$$I = \left(\frac{V}{37}\right)^{2.8} \quad \text{where } I = \text{Amps}/CM^2, \; V = \text{Volts/mil}$$

5) Area - larger area gives greater power handling ability increased leakage.

6) Thickness - larger thickness gives higher clamping voltage and decreased leakage.

The transient threat from which the hybrid is to be protected can be either a current source or a voltage source. For a current source threat the protection circuitry would be as shown on Figure 26. The circuit values are constrained by the following considerations assuming a one microsecond threat pulse width.

1) Determine Area needed.

   Area, $A > I/100\ A/CM^2$

2) Leakage Considerations for allowable leakage I_{LA} at DC voltage V_{DC} of the circuit.

$$I_L = \left(\frac{V_{DC}/L}{37}\right)^{2.8} \cdot A$$

where

I_L = leakage in circuit

L = thickness of MOV in mils

A = Area in CM^2

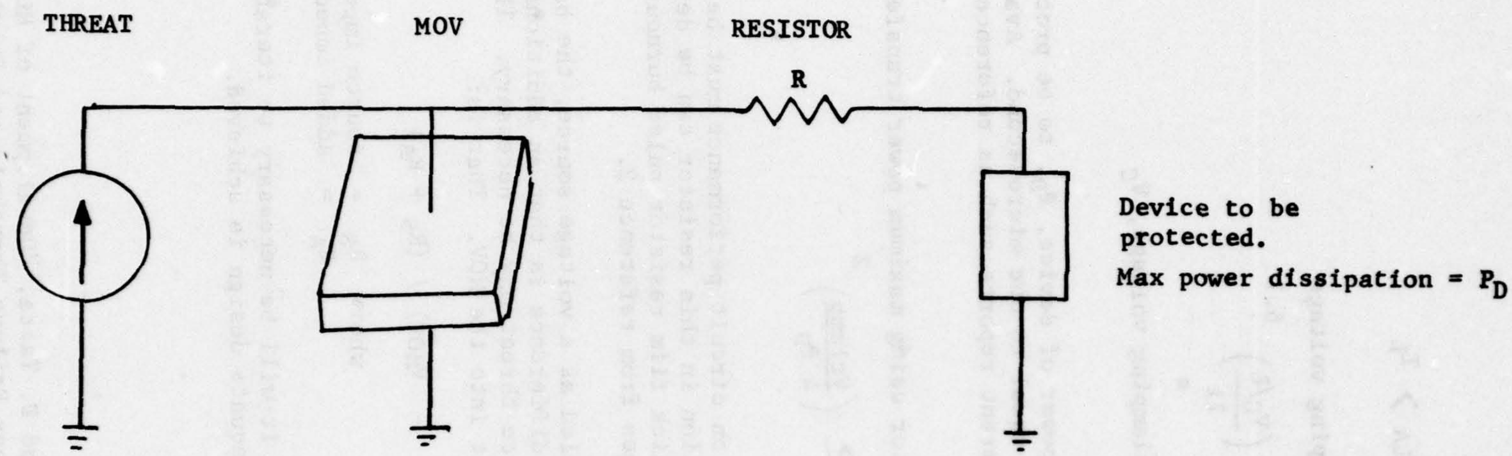


Figure 26

Hybrid Circuit Protection Scheme

adjust L so that

$$I_{LA} > I_L$$

3) Determine clamping voltage

use $$\frac{I_O}{A} = \left(\frac{V_C/L}{71}\right)^{6.7}$$

to obtain the clamping voltage, V_C

4) Obtain damage power of device, P_D, to be protected at pulse width equal to one microsecond. Available from many different reports such as reference 1.

5) Size the resistor using maximum power transfer theorem.

$$R \geq \left(\frac{V_{clamp}}{4\ P_D}\right)^2$$

The effect of this resistor on circuit performance must be determined. The allowable power dissipation in this resistor can be determined by appropriately scaling the thick film resistor pulse burnout data given in Figure 27. This data comes from reference 2.

If the threat is better modeled as a voltage source, the basic procedure is quite similar. The main difference is that an additional resistor between the MOV and the source threat may be necessary. This may be needed to control the current into the MOV. That is:

$$(V_{THREAT} - V_{MOV}) \ / \ (R_S + R_A)$$

where R_S = source impedance
R_A = added impedance

To size the circuit elements it will be necessary to iterate the previous design equations until an adequate design is achieved.

Reference 1. H. O'Donnell and D. Tasca, "Development of High Level Electrical Stress Failure Threshold and Prediction Model for Small Scale Junction Integrated Circuits", General Electric Company, 77SDS4253, Sept. 1977

Reference 2. D. Wunsch, H. Domingos, D. Tasca "Failure Mechanisms in Thick Film Printed Resistors from Electrostatic Discharge and Power Surge Environments", Government Microcircuit Applications Conference, Nov. 1976.

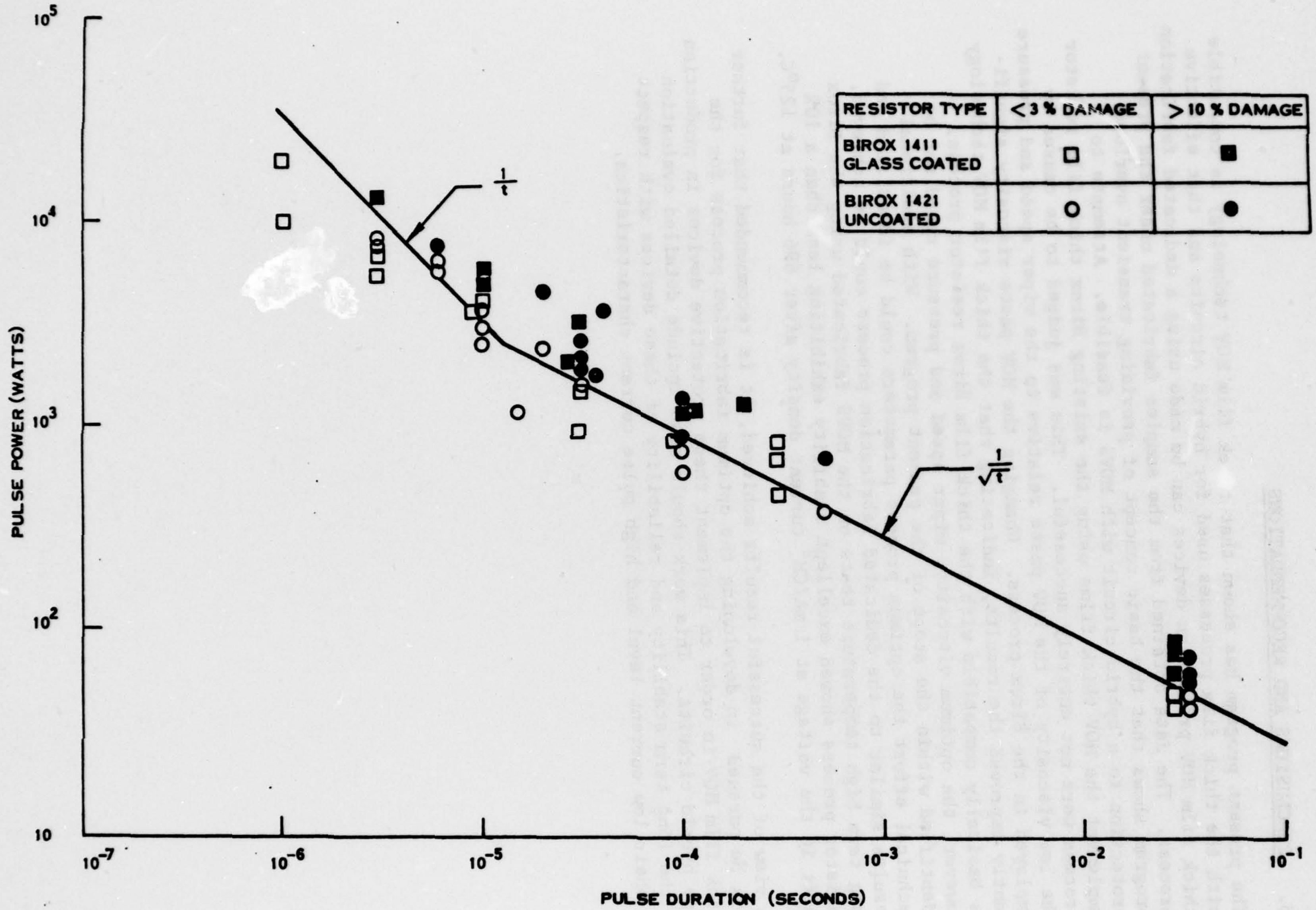


Figure 27. Square Wave Damage Power Dependence on Pulse Width for 40 mil x 120 mil, 0.5 mil Thick Birox 1411 and 1421 Inks Printed on a 25 mil Thick Alumina Substrate

5. CONCLUSIONS AND RECOMMENDATIONS

The present program has shown that thick film MOV technology is compatible with the thick film processes used for hybrid circuits and that effective thick film MOV protection devices can be made using a dedicated fabrication process. The data obtained from the samples fabricated under the present program shows that the basic concept of providing transient overload protection to a hybrid circuit with MOVS is feasible. Attempts to implement the MOV thick films using the existing Birox thick film resistor process were not entirely successful. This was judged to be caused by the low viscosity of the MOV paste relative to the wiper speed and pressure employed in the Birox process. Changing the MOV paste viscosity significantly improved the results, indicating that the thick film MOV technology is basically compatible with the thick film Birox resistor process. However, the optimum viscosity, wiper speed and pressure could not be identified within the scope of the present program. With additional technical effort the optimum process parameters could be identified and results similar to the dedicated fabrication process could be achieved. Long term high temperature tests on the MOVS fabricated using the Birox resistor process showed excellent stability exhibiting less than a 10% shift in the voltage at 1 mA/CM^2 current density after 696 hours at $125^{o}C$.

In view of the successful results achieved, it is recommended that further work be pursued in developing the optimum fabrication process for the thick film MOV in order to implement these protective devices in production type hybrid circuits. This work should also include detailed evaluation of the long term stability and reliability of these devices with respect to their low current level and high pulse current characteristics.

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